



CERN-EP/80-16
7 February 1980

LARGE TRANSVERSE MOMENTUM

HADRONIC PROCESSES

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To be published in
Annual Review of Nuclear and Particle Science



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1. - A HISTORICAL SURVEY

The decade which just elapsed has witnessed drastic changes in our understanding of deep hadronic structure and of strong interaction dynamics. The study of the production mechanism of large transverse momentum hadrons in hadron-hadron collisions, hereafter abbreviated as LPTH (for large p_T hadrons), has been a major -if perhaps not spectacular- contributor to this evolution.

I shall introduce the subject in the form of a historical survey of the progress achieved over the last decade. Being an experimentalist I shall only retain, among the theoretical ideas which blossomed in this field, those which were particularly efficient - owing to their strong predictive power - at motivating and emulating experimental efforts.

1.1 The sources

In the mid sixties, despite the many successes of the quark model (Dalitz 1965) in describing the spectroscopy of hadrons, their electromagnetic properties and the symmetries of their weak decays, serious attempts to understand strong interactions in terms of quark dynamics were still discouraged by the apparent complexity of available experimental data. Possible connections between LPTH and the electromagnetic proton form factors had been discussed by Wu and Yang (1965) but they remained of a rather speculative nature.

It was not until 1969 that a spectacular breakthrough took place : stimulated by recent electroproduction measurements in the deep inelastic region (Panofsky 1968, Breidenbach et al 1969), Bjorken (1969) formulated the scaling behaviour of the nucleon structure functions and Feynman (1969) proposed the parton model according to which a hadron, when viewed in a frame in which it has infinite momentum, is composed of independent point-like constituents (partons). An explicit parton model of the nucleon with "valence" quarks and "sea" quark-antiquark pairs was presented by Bjorken & Paschos (1969) and later supported by the results of neutrino experiments (Eichten et al 1973).

At the same time the CERN Intersecting Storage Rings (ISR) were coming in operation, offering a new possibility to probe short range hadron-interactions and to compare their results with those of deep inelastic leptonproduction (Berman & Jacob 1970).

The parton picture provided a framework in which to formulate efficiently such comparisons. The main properties of LPTH could be outlined independently from the exact nature of the partons and of their interactions : a systematic investigation along these lines was presented by Berman, Bjorken and Kogut in 1971.

1.2 LPTH and the parton model

In parton models (Berman, Bjorken & Kogut 1971, Ellis and Kislinger 1974) LPTH result from the binary collision of two incident partons which carry significant fractions of the colliding hadron momenta (Figure 1). The remaining partons act as spectators and final state interactions play a minor role, even when - as is the case for quark partons - their presence is necessary to redistribute quantum numbers among the collision products. Three ingredients are therefore necessary for a complete description of the collision process : the parton wave functions within the colliding hadrons, the scattering matrix describing the binary parton collision and the fragmentation functions of the scattered partons. The contribution of the hard scattering, which takes place over a very short time scale factors out from that of the other, slower, processes.

The parton wave functions are assumed to obey Bjorken scaling : their dependence upon the incident hadron momentum P_{inc} and upon the longitudinal parton momentum k_L is reduced to a dependence upon the single scaling variable $x = k_L/P_{inc}$; deep-inelastic leptonproduction data suggest that x -distributions take the form $F(x)/x$ where the structure function $F(x) \rightarrow 0$ when $x \rightarrow 1$. The presence of x in the denominator is associated with the development of a rapidity plateau. Dependence upon \vec{k}_T , the transverse parton momentum, is assumed to be strongly damped, with $\langle k_T \rangle \sim 300$ MeV/c in accordance with the observed properties of typical hadronic final states.

The parton fragmentation functions depend, of course, very much on the nature of the partons ; in the case of quark partons, Berman, Bjorken & Kogut (1971) conjectured a behaviour similar to that of the incident wave functions : the hadron fragments have limited transverse momenta with respect to their parent parton and carry a fraction z of its momentum ; z -distributions are independent of the actual value of the parton momentum and take a form $G(z)/z$, with $G(z)$ similar to $F(x)$.

As a result of these simple assumptions fixed angle inclusive cross-sections exhibit scaling properties when expressed as functions of $x_T = 2 p_T \cdot s^{-\frac{1}{2}}$ where p_T is the transverse momentum of the produced hadron and $s^{\frac{1}{2}}$ the total c.m. energy ($\approx 2 P_{inc}$). In particular when the parton-parton interaction is mediated via the exchange of a photon or of a vector gluon, p_T and $s^{\frac{1}{2}}$ are the only momentum scales of the problem and the invariant cross-section for production of a hadron h with 4-momentum (E, p) at angle θ reads

$$E \frac{d^3}{dp^3} \sigma (h_1 + h_2 \rightarrow h + \dots) = s^{-2} f(x_T, \cos\theta) = p_T^{-4} g(x_T, \cos\theta).$$

Many outstanding properties of the final state structure proceed directly from the parton picture. In particular the large transverse momentum products are expected to appear along two directions coplanar with the incident beams (the momenta of the scattered partons), resulting in a "double-core" or "double-jet" pattern. While the jets are predicted to have opposite azimuths, their polar angles may differ widely due to the possibility for the parton-parton system to have a large longitudinal momentum.

The spectator partons are expected to produce a set of hadrons with limited transverse momenta with respect to the incident beams and with smooth rapidity distributions.

1.3 The ISR discovery : LPTH within reach

It was in such a context of ideas that three ISR groups (Alper et al 1973a, Banner et al 1973 and Büsler et al 1973), while measuring single-particle inclusive cross-sections in the large transverse momentum region, observed much larger yields than was commonly expected from a naive extrapolation of the low p_T exponential behaviour. This result came as a surprise : in spite of the success of the quark-parton model in describing deep inelastic leptonproduction results, hadronic processes were still considered by most physicists as belonging to a different chapter of physics with its own specific laws. Instrumentation at the CERN ISR and at the newly operational Fermilab synchrotron was indeed quite inadequate to tackle LPTH experiments ; this lack of experimental preparation has been a severe handicap and it took several years until adequately instrumented detectors became available. The ISR discovery nonetheless demons-

trated the feasibility of exploring the large p_T region with existing machines and immediately triggered a large experimental effort.

The data of Büsser et al (1973) are shown in Figure 2. Invariant cross-sections for the process $p + p \rightarrow \pi^0 + \dots$ are displayed versus p_T , the π^0 transverse momentum, for several values of the total c.m. energy $s^{\frac{1}{2}}$. The measured spectra are much less steep than exponential and are well described by a form (units are GeV and cm^2)

$$E \frac{d^3}{dp^3} \sigma = (1.54 \pm 0.10) 10^{-26} p_T^{-(8.24 \pm 0.05)} \exp(-(26.1 \pm 0.5)x_T).$$

At the same time as the observation of x_T -scaling suggested the validity of the parton model in describing LPTH, the value $-(8.24 \pm 0.05)$ obtained for the exponent of p_T seemed to discourage simple interpretations in terms of point-like parton interactions.

1.4 Mesons as partons

For several years the development of new models has been dominated by the impact of this important result. An immediate effect was to bring into fashion the constituent interchange model of Blankenbecler, Brodsky and Gunion (1972 a and b, 1973 a and b) which predicted scaling $\propto p_T^{-8}$. This prediction was based on the remark that the contribution of sub-processes such as

$$m + q \rightarrow m + q$$

where m and q stand for meson and quark partons respectively, might be dominant in LPTH. The reason is that mesonic partons, say pions, would not be revealed in leptoproduction experiments where the contribution of subprocesses such as

$$m + e \rightarrow m + e$$

is strongly depressed by the presence of the meson form factor. In LPTH instead the interaction can take place via quark exchange, eg

$$\pi^+ + d \rightarrow \pi^0 + u.$$

A convenient framework in which to discuss such processes was provided by the dimensional counting rules (Brodsky and Farrar 1973 and 1975, Matveev, Muradyan & Tavkhelidze 1973) which relate the inclusive cross-section for the reaction $h_1 + h_2 \rightarrow h + \dots$ to the number n_a of "active" quark lines taking part in the hard scattering process and the number n_p of "passive" quark lines wasting momentum in the hadron \leftrightarrow quark transitions

(Figure 3). According to these rules, the fixed angle cross-section takes the form

$$E \frac{d^3\sigma}{dp^3} (h_1 + h_2 \rightarrow h + \dots) \propto (p_T^2)^{-(n_a-2)} f(x_T)$$

with

$$\text{Lim}_{x_T \rightarrow 1} f(x_T) = (1 - x_T)^{(2n_p-1)} .$$

A variety of other subprocesses have been considered, as in the quark-fusion model of Landshoff and Polkinghorne (1973 a, b and c). The many successes of these approaches in describing the scaling behaviour of LPTH cross sections and the hadron form factors have been reviewed by Siverson, Blankenbecler and Brodsky (1976). For a number of years one was led to believe that several subprocesses with $n_a \geq 6$ could be at play in LPTH while the simple quark-quark subprocess ($n_a = 4$) would have played no role in the explored range of p_T and $s^{\frac{1}{2}}$.

1.5 The structure of LPTH final states

Experiments aiming at an analysis of the structure of LPTH final states were conducted at the CERN ISR as soon as it was realized that the relatively large LPTH cross sections made them feasible. It took however four years until a clear picture could emerge. Apart for the lack of adequately instrumented detectors, such experiments had to face two additional difficulties : the necessity to use very large transverse momentum triggers to differentiate between the spectators and the collision products directly involved in the hard scattering process ; and the distortion of the event structure resulting from the use of single particle triggers rather than jet triggers.

The first of these difficulties is inherent to LPTH and contrasts with the much cleaner situation in e^+e^- annihilation or leptonproduction experiments. For a produced particle to be unambiguously assigned to a large transverse momentum jet its transverse momentum must exceed 0.5 GeV/c, or even better 1 GeV/c. This implies that soft jet fragments will never be uniquely identified as such and that very large transverse momentum jets are necessary to permit the observation of a reasonable fraction of their fragments. Experimenters have devoted much effort to constructing detectors providing larger and larger transverse momentum triggers : this

has been a strong element of progress in the LPTH history. For the same reason the highest energy accelerators are best suited to LPTH studies and I shall restrict the present review to Fermilab and ISR data.

The second difficulty can be overcome by using jet triggers rather than single-particle triggers. This is indeed what has been done at Fermilab in recent years using hadron calorimeters with much success. At the ISR, however, the implementation of a jet trigger is a difficult experimental problem : hadron calorimeters have lower performance at smaller energies (a same c.m. transverse momentum appears much larger in the laboratory at Fermilab than at the ISR) ; in addition none of the existing ISR detectors could conveniently accommodate such a calorimeter (it was not until 1979 that a detector (R807) optimised for LPTH studies could be installed at the ISR ; it is expected to operate in 1980). As a result ISR data suffer from the so-called trigger bias effect (Bjorken 1974, Jacob and Landshoff 1976) : since the jet-production cross section has a much steeper p_T dependence than the fragmentation process, it is very likely for a particle of given p_T to be a leading fragment of a relatively soft jet. The resulting artificial asymmetry between the trigger-jet and its partner, the "away-side jet," makes it difficult to reveal their similarities.

It is instructive at this stage to briefly review the main properties of the LPTH event structure as they were known to us towards the end of 1976, excellent reviews of which are available in the literature (Ellis and Stroynowski 1977, Jacob and Landshoff 1978).

Figure 4 shows the particle density phase-space distribution averaged over several LPTH interactions.

i) A large fraction of the particles produced are unaffected by the large transverse momentum process. They retain the main properties of "normal" events in which no large p_T particle is produced. However their longitudinal momentum distribution does not exhibit the so-called "diffraction peak" associated with some low multiplicity interactions. They are associated with the spectator fragments.

ii) The large transverse momentum trigger particle is often accompanied by another particle, at small angle to it, and having a transverse momentum distribution somewhat broader than in single particle inclusive spectra. When expressed in terms of a correlation coefficient at fixed

p_T , this corresponds to very large values - one or two orders of magnitude - because of the steep fall of the production spectra. The presence of strong $\pi^0-\pi^0$ correlations indicates that resonances do not play a dominant role. The rapidity gap between the trigger and its companion decreases when the trigger transverse momentum increases as if both particles were members of the same jet.

iii) An increased particle density is observed in an azimuthal wedge opposite to the trigger particle over a wide range of polar angles. Their coplanarity with the incident protons and the trigger improves when the trigger transverse momentum increases and they exhibit strong transverse momentum correlations with the trigger. Their jet structure is only apparent when each event is considered separately, and for this reason was not immediately recognized : the jet axis spans a wide rapidity range, which broadens the particle density distribution when several events are considered together.

These features supported a qualitative interpretation in terms of a parton model : both jets had been identified and the remaining collision products could be assigned to the spectator partons. At the same time progress had been reported in the study of hadronic final states of e^+e^- annihilations, revealing their jet structure (Hanson et al 1975). This encouraged many semi-quantitative analyses of the LPTH results which strongly confirmed the validity of the parton picture (Bjorken 1975, Ellis, Jacob and Landshoff 1976, Ranft and Ranft 1976, Baier et al 1977, Kripfganz and Ranft 1977, and many others). Moreover quark-quark scattering was usually favoured over quark-meson scattering : the dissimilarity observed between the trigger jet and the away-side jet was found consistent with the trigger-bias effect but could not be accounted for by constituent interchange models having a meson and a jet rather than two jets in the final state.

1.6 The advent of quantum chromodynamics

In order to reconcile the successes of the constituent interchange model in accounting for the scaling properties of inclusive cross-sections and the successes of the quark-parton model in describing the final state structure several authors suggested that quark-quark scattering could indeed be the dominant subprocess if instead of being mediated via vector

gluon exchange it were not scale free ; in particular Hwa et al (1976) noted that the same effective quark-form-factor would account for the scaling violation measured in deep inelastic leptonproduction and for the p_T^{-8} dependence of LPTH cross-sections (see also Contogouris and Gaskell 1977). At the same time the Caltech group (Feynman, Field and Fox 1977, Field and Feynman 1977 and 1978) undertook a major phenomenological analysis of a vast amount of data (LPTH, leptonproduction, e^+e^- annihilation) following a similar approach : they postulated for the quark-quark scattering cross-section an ad-hoc form :

$$\frac{d\sigma}{dt} = \frac{2300 \text{ mb GeV}^6}{st^3}$$

where $s^{\frac{1}{2}}$ and $(-t)^{\frac{1}{2}}$ are the total energy and momentum transfer in the c.m. system of the two quarks. A common outcome of such studies was the necessity to allow for large internal transverse momenta in the quark wave function, up to about 1 GeV/c (Levin and Ryskin 1976, Della Negra et al 1977).

From then on progress has been very fast, both on the experimental and on the theoretical fronts.

A new generation of experiments has come to fruition at Fermilab and at the ISR. At Fermilab two experiments using hadron calorimeters have produced results which have been extensively studied. It had been noted very early (Bjorken 1973, Selove 1972) that the geometry of fixed target machines is well suited to use efficiently hadron calorimeters in order to provide a bias-free trigger on a whole jet. The technique has now proven to be successful and has allowed for direct measurements of jet production cross sections.

At the CERN ISR (Figure 5), experiments have been conducted with much larger transverse momentum triggers than before, up to 16 GeV/c. As a result the p_T^{-8} scaling law has been found unable to describe inclusive cross sections in the larger p_T region where lower powers (typically p_T^{-6}) are measured : one could then hope to start sensing the gluon exchange quark-quark diagram (Clark et al 1978a, Angelis et al 1978, Kourkoumelis et al 1979b). In addition adequately instrumented detectors have become available, opening the door to detailed measurements of the jet properties.

At the same time hadronic final states have been the subject of careful studies in neutrino interactions, deep inelastic leptonproduction

and e^+e^- annihilation data and have revealed the role played by gluons.

On the theoretical front the formulation of QCD as a gauge theory of strong interactions has given an unprecedented impetus to our understanding of their dynamics. The suggestion that gluons could play a dominant role in strong interaction dynamics, suggestion which was supported by the observation in deep inelastic neutrino interactions of a missing longitudinal momentum to the quark partons (Eichten et al 1973, Deden et al 1975) was taken very seriously in 1973 when Politzer (1973) and Gross and Wilczek (1973) showed the existence of a class of Yang-Mills gauge theories which behave, up to calculable logarithmic corrections, as a free-field theory. It was then attractive to imbed strong interactions in such a theory based on coloured quarks and coloured octet-gluons (Fritzsch, Gell-Mann and Leutwyler 1973). It took some years for QCD calculations to show their ability to describe deep-inelastic leptonproduction and e^+e^- annihilation data, during which LPTH experiments had become mature and could be considered in a more fundamental framework than that provided by the ad-hoc approaches mentioned at the beginning of this section. Cutler and Sivers (1977) and Combridge, Kripfganz and Ranft (1977) realized that the one gluon exchange quark-quark term, once renormalized for QCD corrections, could at least partially account for the p_T^{-8} scaling law measured at the ISR below $p_T = 8$ GeV/c. Many subsequent QCD calculations have tackled seriously the problem of describing LPTH data : their successes make it reasonable to hope for a unified description of the various processes probing the deep hadronic structure. I shall try, within the very narrow limits of my competence, to comment briefly on these in Section 3 after having presented the main experimental results in Section 2. For the time being the following superficial remarks should be sufficient.

Inclusive cross-sections are now understood over the whole explored range of p_T . If vector gluon exchange is restored as the basic quark-quark interaction, quark-gluon and gluon-gluon interactions play a dominant role over much of the p_T range. Gluon bremsstrahlung is an important ingredient and its relevance to the description of LPTH final states is essential. While the crudeness of perturbative QCD calculations and the lack of a precise knowledge of the gluon structure functions and fragmentation functions preclude very accurate predictions, it is commonly believed

that all observed features of LPTH will soon be understood in the QCD framework. Constituent interchange processes, which are associated with higher-twist effects in QCD, can still play a significant role at moderate p_T .

2. - EXPERIMENTAL RESULTS : A SUMMARY

It is outside the scope of this review to give a fair and complete account of all LPTH data. I have tried in the Appendix to provide the reader with a detailed list of published experimental results* including brief descriptions of the corresponding detectors. In the present Section I shall rather select a few -usually recent- experiments, which illustrate the present state of our knowledge.

This Section owes very much to the recent and excellent reviews of Di Lella (1979), Jacob (1979) and Selove (1979).

2.1 Single particle inclusive cross-sections

Single particle inclusive cross-sections have been the subject of numerous measurements both at the ISR and at Fermilab. ISR measurements benefit from the large available energy range, well adapted to scaling studies, but are restricted to p-p collisions. Fermilab experiments provide instead flexibility in the choice of the initial state and can be performed with relatively smaller solid angle detectors but they cannot reach as large energy values.

Very high values of p_T , up to 16 GeV/c have been reached in three recent ISR measurements (CS, CCOR, ABCS) of the $pp \rightarrow \pi^0 + \dots$ cross section in the central region. This channel has always been favoured by ISR experimenters owing to the high performance of electromagnetic calorimeters (lead-glass, lead-liquid argon sandwiches) in detecting π_0 's over large solid angles with a good energy resolution and a high rejection power against other hadrons.

Earlier measurements of the π inclusive production cross section had been analysed in terms of parton models in which ad hoc scaling-violations, inspired from the results of deep inelastic leptonproduction

* In the course of the present Section reference is often made to experimental collaborations by means of their acronym : the reader will find the corresponding references in the Appendix.

data, had been introduced (Hwa, Spiessbach and Teper 1976, Feynman, Field and Fox 1977, Field and Feynman 1977, Contogouris, Gaskell and Nicolaidis 1978a, Fishbach and Look 1977 a, b, c, Duke 1977).

The success of these approaches had led Cutler and Sivers (1977) and Combridge, Kripfganz and Ranft (1977) to point out that a QCD calculation including all gluon corrections to the quark-quark Born term could yield the same result. The new ISR measurements have given the opportunity to test the validity of such QCD approaches in a much larger range of p_T . The calculations (Owens, Reya and Glück 1978, Contogouris Gaskell and Papadopoulos 1978, Field 1978, Halzen, Ringland and Roberts 1978) include some or all of the following factors: quark-quark, quark-gluon and gluon-gluon terms, parton transverse momentum k_T distribution, Bjorken scaling violation in the fragmentation and structure functions. The structure functions and their scaling violations are taken from QCD analyses of lepton production data but gluon distributions and parton transverse momentum distributions are educated guesses. The results (Figure 6) show the role played by gluons in part of the p_T range. They are not very sensitive to the k_T distribution, in particular at larger p_T and \sqrt{s} . The reasonable agreement achieved is very encouraging indeed.

It is now clear, as had been suspected long ago, that a scaling form of the type

$$I(x_T, p_T) \equiv E \frac{d^3\sigma}{dp^3} = p_T^{-n} f(x_T)$$

$$\text{or } J(x_T, s) \equiv E \frac{d^3\sigma}{dp^3} = s^{-n/2} g(x_T)$$

is inadequate to describe the data over the whole explored range. In fact, the function

$$n(x_T, p_T) = - \frac{p_T}{I} \frac{\partial}{\partial p_T} I(x_T, p_T)$$

$$\text{or } n(x_T, s) = -2 \frac{s}{J} \frac{\partial}{\partial s} J(x_T, s)$$

is observed to decrease when p_T , x_T , and/or s increase (CCOR). The data suggest that it may approach 4, the perturbative value, when the collision gets harder (Figure 7).

Recent Fermilab experiments (CP, CLFCI) using an incident π^- beam

illustrate well how informative can be the availability of a different initial state. The measurement is of the ratio of the inclusive cross-sections for π^- and π^+ production in π^-p collisions. It is considered as a crucial test of the constituent interchange model which obviously predicts very large values for this ratio. The data show instead a value close to unity in good agreement with QCD predictions (Figure 8). The π^+/π^- ratio has also been measured in p-p and p-n collisions (CP). As expected from most hard-scattering models it increases with x_T in p-p collisions and remains equal to unity in p-n collisions (Owens, Reya and Glück 1978).

The production of particles other than pions has been the subject of many measurements (CP, BS). These include stable particles (K^\pm , p^\pm , η) as well as resonances (ρ , ω , K^*). In particular the η/π^0 ratio has been measured up to $p_T = 11$ GeV/c and found equal to 0.55 over the whole range (ABCS).

Unfortunately most available data on particle ratios are restricted to a region of moderate p_T : it may well be that the regime at which reliable QCD perturbative calculations can be performed has not yet set in. In particular the trigger bias effect would enhance minor contributions from higher twist subprocesses, the QCD analogue of constituent interchange, with respect to quark fragmentation (Blankenbecler, Brodsky and Gunion 1978 , Jones and Gunion 1979). In this context Gustafson and Mansson (1979) studied the scaling behaviour of the cross-section difference between K^+ and K^- production (BS, CP) and found a $p_T^{-5.4}$ law ; since QCD scale breaking effects are expected to partially compensate in the cross-section difference they consider this as a support for quark-quark scattering.

Proton production data are especially disturbing : they are an order of magnitude above QCD estimates using fragmentation functions deduced from $e^+e^- \rightarrow p\dots$ (Owens 1979 a) while their scaling behaviour is well described by the constituent interchange model ; even if this disagreement is nothing but an illustration of our inability to perform accurate QCD calculations, it deserves serious attention. Other modes of proton formation have been considered by Escobar (1979) and Chih Kwan Chen (1978). In general baryon production is not well under control : Bjorken (1975) had already noted the relation

$$(p/K^+) \approx 4 (\bar{p}/K^-)$$

measured in p-p collisions at $p_T = 3$ GeV/c instead of the expected $(p/K^+) \approx (\bar{p}/K^-)$.

A few measurements of single particle inclusive production have been performed at forward angles (NN, CCHK, BCB). Their main conclusion is the validity of "radial" scaling : the angular dependence is accounted for by simply replacing x_T by $x_R = (x_T^2 + x_L^2)^{1/2}$ in the 90° data.

I conclude this brief review of inclusive cross-section data with direct photon production. This channel is of particular interest and its study, which is just starting, should develop into a very rich source of informations. Direct photon production is expected to be rather copious on very general grounds ; photons are electromagnetically coupled to quarks and their weaker coupling is compensated by the fact that they do not fragment : the γ/π ratio is expected to increase with x_T , following the decrease of the fragmentation function of quarks and gluons into a pion (Farrar and Frautschi 1976 , Farrar 1977 , Escobar 1975,1977 , Fritzsche and Minkowski 1977).

In perturbative QCD the dominant source in p-p collisions is quark + gluon \rightarrow quark + photon and reliable predictions can be made (Halzen and Scott 1978 a, b , Llewellyn Smith 1978 a, Rückl, Brodsky and Gunion 1978 Contogouris, Papadopoulos and Hongoh 1979 , Frazer and Gunion 1979 , Jones and Rückl 1979).

Three measurements of the γ/π^0 ratio (ABCS, CRB, FJH) have been published recently ; it may be premature to formulate quantitative comments on these new results but the important point is that a clear and unambiguous signal has been observed (Figure 9), a great progress over earlier inconclusive attempts (the identification of direct photons over a copious background of decay photons is not a trivial experimental problem). The large measured values (γ/π reaches 30 % at $p_T = 7$ GeV/c, $s^{1/2} = 62$ GeV) encourage undertaking dedicated experiments in which final states containing a large transverse momentum direct photon are selected ; the angular dependence, the scaling behaviour, the correlation with other large transverse momentum products should be measured for different initial states. The absence of fragmentation and the impossibility of confusion with the spectator debris should make direct photons a most powerful probe of the deep hadronic structure and greatly simplify

the interpretation of experimental results. This contrasts with inclusive hadronic production which implicitly contains the whole complication of the LPTH mechanism.

2.2 The final state structure : some general features

An ideal bias-free LPTH experiment would use a trigger on the total transverse energy E_T generated during the collision. What is often done is to trigger instead on a single large transverse momentum particle, which results in a double bias : a distortion of the mode of fragmentation of the trigger jet and a transverse momentum imbalance between the trigger jet and its partner. In particular one may wonder whether the positive correlation (CCRS) measured between two azimuthally back to back particles is not a pure effect of energy momentum conservation. The ABCS Collaboration overcome this objection by presenting an elegant analysis of $\pi^0\pi^0$ azimuthal correlations which demonstrates the dynamical nature of the two-jet production mechanism : an estimate of E_T is obtained from the missing transverse momentum to the π^0 pair ; it must be noted that this is in fact an overestimate to the extent that some transverse energy is transferred to the spectators, and therefore irrelevant. The azimuthal opening $\Delta\phi$ of the pair is studied in fixed intervals of the estimated E_T : its distribution exhibits two back-to-back peaks as soon as E_T exceeds ~ 10 GeV (Figure 10). Kripfganz and Schiller (1978) have shown that a rough QCD calculation using quark-quark scattering only and ignoring fragmentation gives already a fair account of this result.

Another demonstration of the coplanarity of the large transverse momentum products is given by the CS Collaboration (Figure 11). They measure the density and momentum distributions of charged particles produced over a 30° azimuthal wedge under three different trigger conditions, a π^0 with $p_T > 5$ GeV/c being detected either within the same wedge or at azimuthal differences of 90° or 180° . The data are presented with reference to "normal" collisions, i.e. without any specific trigger requirement. At 90° out of the trigger plane no sign of the hard collision is visible.

We note that both experiments show no indication of 3-jet final states as could be expected from the $qq \rightarrow qqg$ term. Combridge (1978) has pointed out that the observation of such configurations may be very difficult at

the ISR ; in particular a more favourable topology should be that of three coplanar jets, one on one side of the beams, the others at opposite azimuth and separated in rapidity.

The above examples provide good evidence for the coplanarity of the large transverse momentum products but are not sufficient to demonstrate the existence of a jet structure which implies, in addition, collimation in polar angle. Data of the CCOR Collaboration obtained with a solenoid spectrometer triggered on a large p_T (> 7 GeV/c) π^0 provide a good illustration of the polar angle collimation which had been first observed in other experiments (C, CCHK, BFS). The data (figure 12) are for charged particles in the azimuthal hemisphere opposite to the trigger (away-side particles). No angular correlation is observed with the trigger, which belongs to the other jet ; but a clear correlation with the away-side particle having the largest transverse momentum (the leader) is in evidence ; the jet collimation is observed to increase with the leader transverse momentum indicating that jet fragmentation proceeds with limited transverse momentum with respect to the jet axis.

The general features of the event structure have been successfully reproduced by a number of phenomenological analyses based on the parton model (see Section 1.5). The introduction of scaling violation in the structure functions (Contogouris and Gaskell 1977, Contogouris, Gaskell and Nicolaidis 1978b) and of QCD effects (Feynman, Field and Fox 1978) improve the agreement with the data.

Having briefly illustrated the main features of LPTH events I now turn to a more quantitative analysis of their properties.

2.3 Jet fragmentation

Let us first consider internal jet properties depending only upon their mode of fragmentation, not of formation. The away-side jet, partner of the trigger jet, is often best suited for such studies : it is free of trigger bias while in the trigger jet resonance production is enhanced and may produce large effects even if it corresponds to a small branching fraction.

A global information on the fragmentation mechanism is provided by Fermilab measurements (CLFCI, FLPW) of the jet to single particle cross

section ratio. This is a large quantity, typically two orders of magnitude, increasing with x_T . It is particularly sensitive to the detailed behaviour of the fragmentation function near $z = 1$. The data (Figure 13) are in good agreement with the results of a QCD calculation.

Measurements of the jet multiplicity, including both neutral and charged fragments, have been performed at the CERN ISR (CS). They are compared in Figure 14 with data from e^+e^- annihilation and Up interactions. A similar dependence upon energy, approximately logarithmic, is observed in the three cases.

It is experimentally difficult to identify all particles in an LPTH final state : information on particle ratios within a jet is rather crude. The positive to negative charge ratio, R , has been measured in several experiments and observed to increase with z ; charge correlations among the jet fragments have also been studied. In the absence of correlation, the charge combinations $(++)$, $(^+ \bar{+})$, $(--)$ would be populated in the proportion $R^2 : 2R : 1$. The ratio $\rho = (^+ \bar{+}) / (2 \sqrt{(++)(--)})$ is therefore a measure of the charge correlation, $\rho = 1$ corresponding to no correlation. For the pair of leading charged fragments in each jet the values $\rho = 1.52 \pm 0.05$ and $\rho = 1.60 \pm 0.03$ have been reported for the trigger jet and away-side jet respectively. This observation that opposite charge pairs are favoured in the fragmentation chain agrees with any model in which hadronisation proceeds via production of successive $q\bar{q}$ pairs (Field and Feynman 1978, Andersson, Gustafson and Peterson 1978b) and suggests similarities between the quark and hadron fragmentation mechanisms (Hoyer et al 1979, Andersson, Gustafson and Peterson 1977 and 1978a, Hayot and Jadach 1978).

The BFS Collaboration has performed extensive studies of trigger jets in which the trigger particle is identified. The mean associated momentum for charged secondaries is small because of the trigger-bias effect. Its dependence upon p_T is shown in Figure 15. Such jet configurations are well suited to study the role of resonances, which are relatively enhanced. Data on ρ , K^* and Δ production have been reported.

Having reviewed some global properties of the fragmentation mechanism, let us consider in more detail the behaviour of the fragmentation functions. It is customary to refer the fragment momenta to the total jet momentum \vec{P}_J .

$$\vec{p}_i = z_i \vec{P}_J + \vec{q}_{Ti}, \quad \vec{q}_{Ti} \cdot \vec{P}_J = 0$$

The evaluation of the total jet momentum, and therefore of z and \vec{q}_T , involves an estimate of the contribution of soft fragments which may be confused with the spectator debris : the higher P_{TJ} , the smaller the corresponding correction and the more confidence in the calculation. Measurements of $\langle q_T \rangle$ have been reported by the CCOR and CS Collaborations with the result

$$\langle q_T \rangle = 0.55 \pm 0.05 \text{ GeV}/c$$

for P_{TJ} in the range between 5 and 10 GeV/c (Figures 16 and 17). The CCOR analysis includes in addition a clear demonstration of the axial symmetry of the jet around its axis.

From QCD arguments we should expect two kinds of jets : quark-jets and gluon-jets, with two different modes of fragmentation. On very general grounds (gluons carry a higher colour charge than quarks, importance of the 3-gluon vertex) theoretical studies of gluon jet fragmentation indicate that they should generate high multiplicity final states with soft fragments and no leading flavour (Brodsky, de Grand and Schwitters 1978, Konishi, Ukawa and Veneziano 1979 a and b, Einhorn and Weeks 1978, Kane and Yao 1978, Shizuya and Tye 1978 and 1979). We should also expect $\langle q_T \rangle$, or better $\langle q_T^2 \rangle$, to increase with P_J and develop a high- q_T tail ; a quark-jet should even occasionally be accompanied by a radiated gluon-jet. None of these is apparent in the data which are not accurate enough, nor span a large enough P_J range to reveal such details. It is nonetheless interesting to compare the LPTH value of $\langle q_T \rangle$ - even if it only contains crude information - with the equivalent quantity measured in e^+e^- annihilation and in νp interactions (Figure 18) : hadron jets from these three different sources are observed to exhibit very similar transverse fragmentation once soft fragments (responsible for the so-called sea-gull effect) are ignored.

The z -dependence of fragmentation functions has been the subject of many measurements. However the z (of away-side fragments) is often referred to the trigger transverse momentum rather than to P_J , in which case it is usually called x_e . This introduces additional complications involving the transverse momentum correlation between the two jets (see Section 2.4). To a good approximation, z -distributions can be described by an exponential

form with the same slope as for e^+e^- jets (Figure 19).

An essential feature of the fragmentation function is its approximate scaling behaviour, namely its independence from P_J . Evidence that this is indeed the case at large enough P_J is overwhelming (Figure 20).

A summary of LPTH data compared with e^+e^- annihilations and $U-p$ interactions is presented in Figure 21.

2.4 Jet-jet correlations

Correlation measurements between the two jets should provide information on the hard-scattering subprocess and on the wave functions of the interacting partons, independently from the fragmentation mechanism.

Quark-quark scattering should produce two jets having uncorrelated charges. This is indeed what is observed in the highest available range of transverse momentum : the charge correlation coefficient ρ defined in the preceding subsection has been measured between the leading charged fragments of jets produced in $p-p$ collisions and found equal to 1.00 ± 0.03 (CS).

At lower transverse momenta some charge compensation between the trigger and the away-jet is however still present (BFS). This again indicates that higher twist effects may play a significant role at moderate p_T 's (Chase 1978a). It is worth noting that a measurement of ρ in e^+e^- annihilations at Petra should reveal the quark-antiquark nature of the final state ; to my knowledge this has not yet been observed.

Direct information on the pion structure functions is provided by a Fermilab experiment (FLPW) which compares the jet production cross-sections for $p-p$ and $\pi-p$ collisions. The ratio between these two quantities is displayed in Figure 22 together with the similar ratio measured for inclusive pion production. It shows that pions are more efficient than protons at producing large transverse momentum jets : pion constituents carry a larger momentum fraction than proton constituents do. This interpretation is confirmed by the angular dependence of the cross-section ratio which is measured to decrease in the forward direction.

Much effort has been devoted in collecting information on the transverse motion of the colliding partons ; the observation that internal transverse momenta k_T of the order of 1 GeV/c were necessary was an outstanding conclusion of early phenomenological analyses.

In the QCD language one is led to distinguish between the "primordial" k_T (associated with the hadron size) and the k_T component acquired from gluon radiative corrections when p_T increases. Their distributions have been the subject of a very large number of theoretical studies, usually in connection with large p_T production of massive lepton pairs in hadron collisions. The situation is somewhat controversial and will be commented upon in Section 3.3. For the time being I shall retain the naive parton model definition of k_T as a convenient means to compare different data.

Direct measurements of the transverse momentum imbalance between the two jets have been reported at Fermilab (FLPW) and at the ISR (CS) ; they indicate an approximately gaussian distribution with ~ 1.2 GeV/c half width at half maximum (Figure 23).

In experiments using a single particle as large transverse momentum trigger it is customary to measure the distribution of the momentum component of the away jet fragments normal to the trigger plane, a quantity called p_{out} . It depends not only upon the transverse motion of the incident partons but also on the transverse fragmentation of the away jet. In fact $\langle p_{out} \rangle$ is expected not only to increase trivially with z , the momentum fraction of the away jet carried by the fragment, but also with the total jet momentum because of the increased gluon radiation. This is indeed what is observed (Figure 24) yielding again $\langle k_T \rangle$ values of the order of 1 GeV/c. Similar values are deduced from the analysis of dilepton production in p-p collisions. I shall return to this result in Section 3.3.

Additional information on jet-jet correlations is provided by measurements of the inclusive cross-section for production of symmetric pion pairs in p-p collisions (CFS, CCOR). The restriction to pions having approximately opposite transverse momenta simplifies the interpretation of the data (Baier, Cleymans & Peterson 1978) : the role played by k_T is reduced. Fermilab data on $\pi^+ \pi^-$ pairs are compared to the result of a QCD calculation in Figure 25a. The same calculation, extended to ISR energies, is compared in Figure 25b to similar data for π^0 pairs. The agreement is quite encouraging.

2.5 The spectators

The debris of the colliding hadrons, after amputation of the two partons taking part in the hard scattering, populate the large rapidity regions. Their observation, in the vicinity of the incident beam (or beams) is not always easy. Several interesting results have been nonetheless collected, which deserve a brief mention.

The density of spectator fragments decreases with increasing transverse momentum of the trigger, more rapidly than could be expected from pure energy-momentum conservation. They are observed to carry a transverse momentum opposite to that of the trigger, typically 100 MeV/c per particle (BFS). This provides additional information on the transverse motion of incident partons and yields an independent measurement of the transverse momentum imbalance between the two jets. Fontannaz, Pire and Schiff (1978) using diquark fragmentation functions obtained from deep inelastic leptonproduction data (in the target fragmentation region) show that the BFS results are consistent with the following simple picture : one of the proton valence quarks is kicked out at large p_T and the left-over diquark travels along and fragments according to the same mechanism as in leptonproduction.

Data taken with a forward large transverse momentum trigger provide a means to identify the incident hadron from which the trigger jet originates (CCHK). They show strong correlations between the trigger and its parent proton but none with the other incident proton. Moreover these correlations, when studied for different types of trigger particles, are well understood from simple dimensional counting arguments.

3. - LPTH AND OTHER DEEP-HADRONIC PROBES

3.1 Future prospects

In the course of the preceding section we had many opportunities to compare LPTH data either with the results of perturbative QCD calculations or with measurements performed in e^+e^- and Up experiments. Emphasis has been put on the successes of the QCD approach, at the risk of appearing somewhat biased in its favour. The motivation in doing so was not to

oversimplify a rather complex experimental reality. But the difficult LPTH experiments, with complicated multibody final states, require guidance to suggest relevant measurements and efficient modes of data presentation. Such a guidance is presently best provided by the QCD approach which is the most successful at describing existing data and possesses a strong predictive power. The hope to reach in the QCD framework a coherent and unified description of strong interaction dynamics is an important stimulus to encourage further experimental efforts.

Future LPTH prospects are manyfold. The use of higher performance detectors, such as the axial field magnet at the ISR, should help refining the present picture. Whenever possible experiments testing a specific aspect of the interaction should be preferred to those involving its whole complexity. The preceding section gave us many examples of that kind : ratios of inclusive cross-sections measured either with different beams or for different types of produced particles, jet fragmentation studies without reference to the mode of formation, measurements of the transverse momentum imbalance between the two jets independently from their mode of fragmentation, etc... A particularly rich source of information, as yet almost unexploited, is the study of final states containing a large transverse momentum direct photon, the analysis of which should be greatly simplified.

Improvements of the existing machines, namely the availability of $p\bar{p}$ collisions at the ISR and the increase of the Fermilab energy will help in achieving successfully these tasks.

In addition a new unexplored energy domain will soon be within reach with the coming in operation of the SPS $p\bar{p}$ collider in Europe and of Isabelle and the Fermilab collider in the United States. Anticipated jet yields are very large at such machines (Figure 26) and spectacular effects are expected. The availability of measurable cross-sections up to transverse momenta of the order of 50 to 100 GeV/c will allow one to probe hadronic structure much deeper than was previously possible. Even in the small x_T region, accessible with low luminosities, a copious production of gluon jets is expected.

3.2 Deep hadronic probes in the naive parton model

A clear message of the past is that for LPTH experiments to progress they must be constantly confronted with the results of other measurements using different probes : e^+e^- annihilation, deep inelastic leptonproduction,

Drell-Yan dilepton production (Drell and Yan 1970 and 1971). In the preceding Section such comparisons have been made whenever possible and striking similarities were noted. It is instructive at this point to briefly assess the merits of LPTH in this context. A crude investigation in the framework of a naive quark parton model will help drawing the general lines. The more realistic QCD picture will be treated in the next subsection. Four processes are considered together in Table 1 : a) e^+e^- annihilation into hadrons ; b) Drell-Yan production of lepton pairs ; c) leptonproduction experiments in the deep-inelastic region (with incident neutrinos, electrons or muons) ; d) LPTH. In terms of naive quark diagrams a unified description of these processes involves three independent quantities : the structure functions describing the quark content of hadrons, the fragmentation functions describing the hadron content of quarks, and the scattering amplitudes of colliding quarks. The latter can only be inferred from (d) and are irrelevant to the other processes. However the former are best measured in a) and b), to which they contribute uniquely. Disentangling quark-quark scattering amplitudes from d) is therefore likely to require the previous knowledge of the structure and fragmentation functions obtained from simpler processes. It is also apparent from the naive quark picture that the richer information provided by d) is obtained at the price of a higher complexity of the final state. While only two coloured jets have to annihilate their unphysical quantum numbers in the first three processes, four coloured jets are present in d), thereby requiring a more complex set of final-state interactions.

In this too naive picture LPTH appears as the process involving the greatest complication, but it provides some information which is out of reach of the other processes. Similar conclusions apply when considering its role in the QCD framework.

3.3 Deep hadronic probes in the QCD framework

A first, major, question to answer is to which extent does QCD preserve the validity of the naive parton model picture : does the general LPTH event structure persist, does it still make sense to talk about coplanar large transverse momentum jets, about fragmentation and structure functions, about spectator fragments, etc... This has been the

subject of intense theoretical studies during the past three years, which have converged to a set of very important results. A first step was to recognize that the Q^2 -dependence of the moments of the structure functions measured in leptonproduction experiments is amenable to a simple parton model interpretation (Altarelli and Parisi 1977, Kim and Schilcher 1978, Abad and Humpert 1978) : the effects of gluon corrections, such as gluon bremsstrahlung from a quark parton, factor out from the hard scattering between the target and the virtual probe (mass squared = Q^2) : this results simply in a redefinition of the structure functions, which acquire a Q^2 -dependence inducing scaling violation, but preserves the naive parton-model picture. Politzer (1977a) suggested that such a factorization mechanism could occur for processes more complicated than leptonproduction (for which the hadron structure is probed directly by a local current) ; his conjecture was confirmed in particular for quark-quark scattering (Sachrajda 1978a, Furmanski 1978) and for the Drell-Yan process (Politzer 1977b, Sachrajda 1978b). The general proof was soon established (Ellis et al 1979, Amati, Petronzio and Veneziano 1978 a and b, Libby and Sterman 1978 a and b) that for any hard process which admits a parton-model interpretation the effect of QCD interactions to all orders in perturbation theory are simply absorbed in a universal renormalization of the structure and fragmentation functions. In the mean time different theoretical approaches (Sterman and Weinberg 1977, Wosiek and Zalewski 1979, Furmanski 1979, Llewellyn Smith 1978b, and Dokshitzer, D'yakonov and Troyan 1978 a and b) had pointed to similar conclusions.

The factorization of the hard scattering subprocess preserves the validity of the parton model picture ; in particular, for LPTH, all we have to do is to use the running coupling constant $\alpha_s(Q^2) \propto (\text{Log } Q^2/\Lambda^2)^{-1}$, $\Lambda \sim 500$ MeV, and the Q^2 -dependent structure and fragmentation functions measured in leptonproduction and e^+e^- annihilation experiments. This is precisely the approach which has been followed in most QCD calculations mentioned in the preceding Sections and to which LPTH data were confronted.

We may now return to our evaluation of the role of LPTH among other deep hadronic probes and feel justified to continue using the parton model language.

A first remark concerns the hard scattering subprocess : in addition to quark-quark scattering, quark-gluon and gluon-gluon scattering con-

tribute to leading order (Cutler and Sivers 1978, Hagiwara 1979). For each of these terms we need to know the Q^2 -dependent structure and fragmentation functions. Factorization does not imply that the structure function effectively measured in a given hard scattering process can be blindly plugged in a calculation involving another hard scattering process : gluons, sea and valence quarks of various flavours, may play a different role in the two cases and, since each of these is expected to have different structure functions, with different Q^2 -dependences, they will combine differently in the two processes. This trivial remark, which of course applies as well to fragmentation functions, indicates potential difficulties in comparing the reactions listed in Table 1.

In particular gluons are not directly probed in leptonproduction experiments and reliable measurements of their densities are difficult to obtain (Altarelli and Martinelli 1978, Anderson Matis and Myriantopoulos 1978, Glück and Reya 1979, Wu Ki Tung 1978, Mendez and Weiler 1979). LPTH data, if the effect of gluon terms could be easily disentangled, would provide a more convenient means of measuring gluon densities. A particularly interesting channel in this context is direct photon production which is expected to be dominated by the gluon + quark \rightarrow photon + quark term. Meanwhile most QCD calculations of LPTH data have used educated guesses of the gluon densities, relating them to the well known structure functions of the valence quarks (see for example Glück and Reya 1977).

Quark structure functions are available for valence and sea quarks of different flavours as a result of the recent accumulation of accurate leptonproduction data (Gordon et al 1978, Bosetti et al 1978, de Groot et al 1979 a and b, Bodek et al 1979, Fernandez et al 1979, Benvenuti et al 1979). Their Q^2 -dependence is found consistent with QCD predictions ; in fact the observation that the relation between different moments are in quantitative agreement with QCD (Bosetti et al 1978, de Groot et al 1979 a and b) has been considered by many as a spectacular success of the theory although the relevance of this result has recently been contested (Harari 1979, Abbott and Barnett 1979).

Structure functions of particles other than nucleons are not accessible to leptonproduction experiments : their measurement is the privileged domain of LPTH and Drell-Yan processes. A first step in this direction has been taken by the FLPW Collaboration (Dris et al 1979). More, and more

accurate data should become available in the not too distant future.

Fragmentation functions should be most directly obtained from e^+e^- annihilation data (Hanson et al 1975, Berger et al 1979 a and b). However the flavour content of e^+e^- jets is completely different from that of LPTH quark-jets : the latter are expected to be mostly of u and d parentage owing to the dominance of these flavours in the initial state. In e^+e^- annihilations, where copious production of heavy flavours is expected as soon as the corresponding thresholds are open, the experimental problem of identifying the parent flavour is very difficult ; as a result little is known on the flavour dependence of the fragmentation functions. Lepton-production experiments are potentially a rich source of information in this context ; the jet-structure of their final state (quark + diquark) has been observed and detailed measurements of their structure are underway. A possible indication of QCD effects is provided by the observation that $\langle q_T^2 \rangle$ seems to increase with jet momentum in neutrino data (Bosetti et al 1978, Mazzanti Odorico and Roberts 1979).

Much less is known concerning the fragmentation of gluons ; LPTH is the only hard process to which they contribute to leading order but available data do not provide any evidence for gluon jets different from quark jets. However e^+e^- annihilations may be a rich source of gluon jets, either as decay products of heavy γ -onia, or as companions of quark-anti-quark jet-pairs (Ellis, Gaillard and Ross 1976, de Grand, Ng and Tye 1977). Recent PETRA experiments (Barber et al 1979 and Brandelik et al 1979) have provided evidence for their production ; if such an interpretation is confirmed, gluon fragmentation functions might soon be measured at PETRA and PEP.

There have been several very recent attempts to perform QCD calculations of quark and gluon fragmentation functions (Altarelli et al 1979, Konishi, Ukawa and Veneziano 1979 a and b, Shizuya and Tye 1979, Bassetto, Ciafaloni and Marchesini 1979). They show that the properties of the fragmentation mechanism which were intuitively assumed in earlier parton model analyses, in particular the connection between structure and fragmentation functions, are confirmed. However, when it comes to detailed confrontations between theory and experiment, the situation is becoming very complicated due to the presence of different flavours and the role played by resonance formation (Dias de Deus and Sakai 1979).

After these comments we may be surprised by the similarity observed

between LPTH and other jets (Figures 14 and 18) ; it may be accidental or the data may be too crude to reveal the expected differences. More refined measurements are necessary to assess the role of gluon jets in LPTH final states ; the presently explored p_T range may be too low to easily distinguish them from quark jets (Shizuya and Tye 1979, Einhorn and Weeks 1978).

Another essential ingredient in the QCD description of LPTH processes is the transverse momentum distribution (k_T) of the incident partons. If it does not much contribute to single particle inclusive cross sections it plays obviously an essential role in the description of two particle correlations in the "back to back" configuration and of transverse momentum imbalance between the two jets (Owens 1979 b, Owens and Kimel 1978, Alonso et al 1979, Fontannaz and Schiff 1978, Chase 1978 b). Some information on this quantity is in principle available from the lack of collinearity of the quark and diquark jets in lepton production final states, but it is in Drell-Yan production that it has been most extensively studied. Experimentally (Lederman 1978) the transverse momentum distribution of muon pairs produced at Fermilab and at the ISR is observed to be very wide, corresponding to an effective value of $\langle k_T \rangle$ of at least 1 GeV/c in the ISR energy range. Even if part of the effect at Fermilab can be blamed on nuclear complications, this result has caused some surprise and its interpretation has led to much confusion and controversy. The confusing issue is the presence of two short-distance scales in the problem (Kajantie and Lindfors 1978, Caswell, Horgan and Brodsky 1978) : the dimuon mass and its transverse momentum, or, in the case of LPTH, the mean transverse momentum of the jets and their p_T imbalance. How does factorization work in such a case ?

The Drell-Yan term, $q + \bar{q} \rightarrow \gamma^*$, accounts well for the total dimuon production cross-section once scaling violations are introduced in the structure functions according to the factorization prescription (Altarelli, Ellis and Martinelli 1979, Kubar-Andre and Paige 1979) ; higher order terms are dominated by the $q + \bar{q} \rightarrow \gamma^* + g$ correction which contributes significantly.

For large transverse momentum pairs however, terms such as $q + g \rightarrow q + \gamma^*$ are expected to play an important role (Fritzsch and Minkowski 1978, Halzen and Scott 1979, Altarelli, Parisi and Petronzio 1978) even if their

contribution to the total cross-section is minor (Kripfganz and Contogouris 1979, Contogouris and Kripfganz 1979). In this context the experimental observation of a hadron jet balancing the dilepton transverse momentum would be very informative and should provide a way to single out gluon jets (Brucker et al 1978).

Georgi (1979) has recently given a clear analysis of the problem in which he shows that k_T effects can be included in factorized QCD inclusive cross-sections but that k_T is a very complicated variable from the point of view of factorization : the moments of the distribution functions do not factor out at fixed k_T . Recent QCD calculations (Glück and Reya 1978, Soper 1979, Dokshitzer, D'yakonov and Troyan 1978 a and b, Parisi and Petronzio 1979) achieve good agreements with the data ; contrary to the suggestions of earlier analyses they do not require a large primordial k_T : a value of the order of 200 MeV/c is sufficient, the broad distribution of the dilepton transverse momentum being well accounted for by the dynamical recoils.

The extension of the Drell-Yan results to LPTH is not straightforward since different hard-scattering terms are involved both for low and for large p_T imbalances between the two jets. The similarity noted between the effective $\langle k_T \rangle$ values deduced from LPTH data and dilepton production experiments is not expected to resist to a more accurate comparison when better quality data become available.

A last comment concerns the role played by constituent interchange terms which in QCD language correspond to higher twist corrections ; in the course of Section 2 we have met several indications (e.g baryon production, quantum number correlations between the two jets) that they may play a role in LPTH, in particular at moderate values of p_T where they are enhanced by the trigger bias effect. Such terms are not expected to contribute significantly to the other processes listed in Table 1.

This elementary evaluation of the role of LPTH among other deep hadronic probes suggests the following concluding remarks :

- i) QCD has reached a state where it can efficiently guide the choice of future LPTH measurements and offers clear schemes in which to present and analyse their results.
- ii) Most available LPTH data are in agreement with the expectations of QCD calculations, an encouraging stimulus for the future.

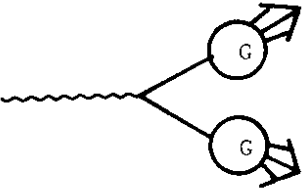
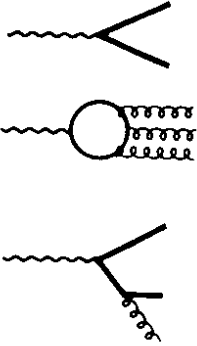
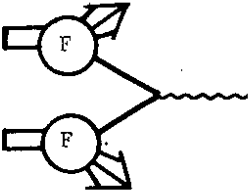
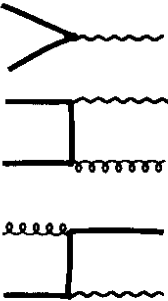
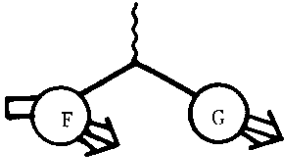
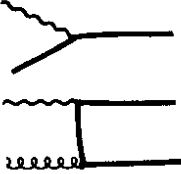
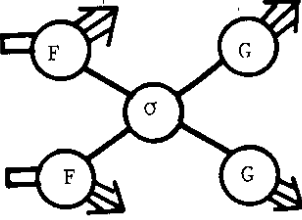
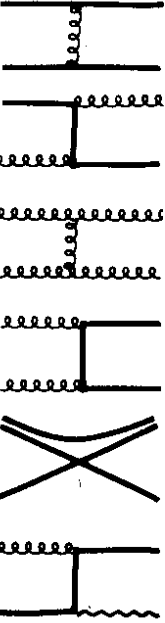
- iii) LPTH is the deep hadronic probe which involves the greatest amount of dynamical complexity. On one hand this implies that its analysis requires the previous understanding of other simpler processes such as e^+e^- annihilation, leptonproduction, Drell-Yan dileptons. On the other hand LPTH offers a unique means to gain access to quantities which are not directly probed in other processes, in particular those related to gluons.
- iv) Wherever possible LPTH results should be formulated in a simple form allowing for specific tests of the theory. Factorization is very suggestive in this context as it simplifies the interpretation of experiments which differ only in a few of their aspects (cross-section ratios, etc...).
- v) Direct photon production is a rich potential source of information. Its relatively simple description in the QCD framework (inasmuch as it is not referred to the more complicated π^0 production) should encourage detailed measurements of the structure of associated final states.
- vi) LPTH and Drell-Yan process benefit from the availability of \bar{p} , K and π beams at fixed target machines : this advantage over leptonproduction experiments gives them the unique possibility to measure the structure functions of these particles.
- vii) In the not too distant future new machines (CERN SPS $p\bar{p}$ collider, Isabelle, Fermilab collider) will be available to explore a new range of transverse momenta, up to ~ 100 GeV/c. LPTH and the Drell-Yan process will have the unique opportunity to probe much smaller distances than previously possible. Even at low luminosity copious production of gluon jets is anticipated.
- viii) The progress of our understanding of strong interaction dynamics requires a constant confrontation between the theory and the results of experiments in which the deep hadronic structure can be probed. LPTH has a major role to play in this context and it should never be "the neglected stepchild of the quark-parton model" as Cutler and Sivers (1977) once called it. Higher order QCD effects are known to be important, for example in the Drell-Yan process where they induce a renormalization of the cross-section by a factor of almost 2. LPTH offer another laboratory in which they can be measured.

ACKNOWLEDGEMENTS

I am deeply indebted to L. Di Lella, J. Ellis and M. Jacob who have contributed very useful comments to this review. In particular I owe much to the recent rapporteur talks of L. Di Lella (1979) and M. Jacob (1979) and to illuminating discussions with their authors.

I wish to thank Michèle Jouhet for her help to bring this report to its present form.

TABLE 1 : DEEP HADRON PROBES

Process	Naive parton model	Some relevant QCD terms (excluding scaling violations)
a) e^+e^- annihilation		 <p> $\gamma \rightarrow q\bar{q}$ (leading) $\gamma \rightarrow \text{onium} \rightarrow 3g$ $\gamma \rightarrow q\bar{q}g$ </p>
b) Drell-Yan pairs		 <p> $q\bar{q} \rightarrow \gamma$ (leading) $q\bar{q} \rightarrow \gamma g$ $qg \rightarrow q\gamma$ </p>
c) Deep inelastic lepton production (γ, Z, W)		 <p> $\gamma q \rightarrow q$ (leading) $\gamma g \rightarrow q\bar{q}$ </p>
d) LPTH		 <p> $qq \rightarrow qq$ $qg \rightarrow qg$ $gg \rightarrow gg$ $gg \rightarrow q\bar{q}$ constituent interchange $q+g \rightarrow q+\gamma$ (direct photons) </p>

APPENDIX : EXPERIMENTAL ASPECTS

Table 2 below provides the reader with a brief summary of the main characteristics of the detectors used in LPTH studies. The following abbreviations have been used : SAS for single arm magnetic spectrometer, DAS for double arm magnetic spectrometer, SFMD for Split Field Magnet Detector. Solid angle, polar angle, azimuth and rapidity are denoted Ω , θ , ϕ and y respectively. Collaborations are referred to in the first column by their acronym ; their detailed denomination is given in Table 3.

Table 3 gives a list of publications issued by the experimental Collaborations. Contributions to Conferences have usually been ignored ; they are only retained if not covered by a subsequent Journal publication.

TABLE 2 : DETECTORS

COLLABORATION	BEAM + TARGET	TRIGGER	SECONDARIES
ACHM	p+p	γ , $\Delta\Omega=0.3$ sr, $\theta=53^\circ$, 90° lead glass array	charged hadrons, no momentum analysis, $\Delta\Omega \sim 4\pi$ streamer chambers
ABCS	p+p	γ , ($\Delta\phi=45^\circ$, $\Delta\theta=90^\circ$)x4 Four liquid argon calorimeters (Pb) in various azimuthal configurations	
BFS	p+p	π^\pm , π^\pm , K^\pm , $\Delta\Omega=4$ msr, $\theta=90^\circ$ SAS with Cerenkov counters	charged particles in the SFMD
BS	p+p	π^\pm , π^\pm , K^\pm , $\Delta\Omega=12$ msr, $\theta=36$ to 90° SAS with Cerenkov counters	
BCB	π^\pm , p+p	γ , $\theta = 15$ to 110° Fine grain lead-scintillator sandwich	
CLFCI	π^\pm , K^\pm , p +p, Al, Be	hadron jets, $\theta=\pm 90^\circ$, $\Delta\Omega=2 \times 1.5$ sr Double Arm hadron calorimeter	magnetic spectrometer covering the trigger acceptance (charged particles).
C	p+p	γ , $\Delta\Omega=0.1$ sr, $\theta=90^\circ$ lead glass array	charged particles in the SFMD
CCHK	p+p	h^\pm , $\Delta\phi=20^\circ$, $\Delta y=0.8$, $\theta=9$ to 21° , 45° , geometry selection on straight tracks π^\pm , K^\pm , p, Cerenkov counters, $\theta=20^\circ$	charged particles in the SFMD
CCOR	p+p	γ , $\Delta\Omega \sim 2 \times 1$ sr, $\theta=\pm 90^\circ$ Double arm lead glass arrays	charged particles in drift chamber detector in superconducting solenoid, $\Delta\phi=2\pi$, $\Delta y=1.4$

CCR	p+p	γ , $\Delta\Omega \sim 2 \times 0.6 \text{sr}$, $\theta = \pm 90^\circ$ Double arm lead glass arrays	charged particles, no magnetic analysis, in spark chambers covering the trigger acceptance
CCRS	p+p	γ , $\Delta\Omega \sim 2 \times 0.6 \text{sr}$, $\theta = \pm 90^\circ$ Double arm lead glass arrays	charged particles in DAS covering the trigger acceptance
CRB	p+p	γ , $\Delta\Omega \sim 0.5 \text{sr}$, $\theta = 90^\circ$, lead glass array	
CS	p+p	γ , $\Delta\Omega \sim 2 \times 0.8 \text{sr}$, $\theta = \pm 90^\circ$, Double arm lead glass arrays	charged particles in DAS covering the trigger acceptance
CP	p+p, N	π^\pm , p^\pm , K^\pm , $\theta \sim 90^\circ$, $\Delta\Omega = 20 \mu\text{sr}$ lab, SAS with Cerenkov counters	
CF	p+N	γ , $\theta = 65, 93^\circ$ lead glass array	
CFS	p+Be, W	hadron pairs in DAS with Cerenkov counters for particle identification $\theta = \pm 90^\circ$, $\Delta\Omega = 2 \times 0.063 \text{sr}$	
DLR	p+p	π^\pm , K^\pm , p^\pm , $\theta = 90^\circ$, $\Delta\Omega = 12 \text{msr}$ in SAS with Cerenkov counters	Crude charged particle detection without momentum analysis (spark chambers + scintillators) over $\Delta\phi = 2\pi$, $\Delta y = 3$.
FJH	p+Be	Double arm lead glass spectrometer	
FLPW	π^\pm , p+p	hadron jets, $\theta = \pm 90^\circ$, $\Delta\Omega \approx 1.5 + 2 \text{sr}$ Double arm hadron calorimeter	charged particles in drift chambers covering the trigger acceptance (no momentum analysis)
FMP	p+N	K^\pm in single arm of DAS equipped with Cerenkov counters	
NN	p+p, C (internal)	γ , $\theta = 40$ to 110° , $\Delta\Omega = 9.5 \mu\text{sr}$ lab lead glass array	

PSB	p+p	γ , $\theta=90^\circ$, 17.5° , $\Delta\Omega=0.3\text{sr}$ lead glass array	Crude charged particle detection without momentum analysis over $\Delta\Omega \sim 4\pi$ (scintillators)
SS	p+p	h^\pm , $\theta=90^\circ$, $\Delta\Omega=85\text{msr}$, SAS	

TABLE 3

EXPERIMENTER COLLABORATIONS : PUBLICATIONS

- Aachen - CERN - Heidelberg - München (ACHM)
 - Eggert et al 1975a : A study of high transverse momentum π^0 's at ISR energies.
 - Eggert et al 1975b : Angular correlations in proton-proton collisions producing a large transverse momentum π^0 .
- Athens - Brookhaven - CERN - Syracuse (ABCS)
 - Cobb et al 1978 : Azimuthal correlations of high transverse momentum π^0 pairs.
 - Kourkouvelis et al 1979a : Study of resolved high- p_T neutral pions at the CERN ISR.
 - Kourkouvelis et al 1979b : Inclusive π^0 production at very large p_T at the ISR.
 - Kourkouvelis et al 1979c : Inclusive η production at high p_T at the ISR.
 - Kourkouvelis et al 1979d : Azimuthal correlation of a high p_T π^0 and η with a second π^0 produced in p-p collisions at the ISR.
 - Kourkouvelis et al 1979e : Correlations of high transverse momentum π^0 pairs produced at the CERN ISR.
 - Kourkouvelis et al 1979f : Measurements of π^0 fragments from jets produced in p-p collisions at the CERN ISR.
 - Diakonou et al 1979 : Direct production of high p_T single photons in p-p collisions at the CERN ISR.
- British - French - Scandinavian (BFS)
 - Albrow et al 1978a : Studies of p-p collisions at the CERN ISR with an identified charged hadron of high transverse momentum at 90° .
 - (I) On forward particles in high p_T reactions.
 - Albrow et al 1978b : *ibid.*
 - (II) On the distribution of charged particles in the central region.
 - Albrow et al 1979 : *ibid.*
 - (III) Jet-like structures.
- British - Scandinavian (BS)
 - Alper et al 1973a : Production of high transverse momentum particles in p-p collisions in the central region at the CERN ISR.

- Alper et al 1973b : Particle composition at high transverse momenta in p-p collisions in the central region at the ISR.
- Alper et al 1975a : The production of charged particles with high transverse momentum in p-p collisions at the CERN ISR.
- Alper et al 1975b : Production spectra of π^\pm , K^\pm , p^\pm at large angles in proton-proton collisions in the CERN ISR.
- Brookhaven - Caltech - Berkeley (BCB)
- Donaldson et al 1976 : Inclusive π^0 production at large transverse momentum from $\pi^\pm p$ and pp interactions at 100 and 200 GeV/c.
- Donaldson et al 1978a : Angular dependence of high transverse momentum π^0 production in $\pi^\pm p$ and pp interactions.
- Donaldson et al 1978b : Comparison of high transverse momentum π^0 production from π^- , K^- , p and \bar{p} beams.
- Caltech - UCLA - Fermilab - Chicago Circle - Indiana (CLFCI)
- Bromberg et al 1977 : Observation of the production of jets of particles at high transverse momentum and comparison with inclusive single-particle reactions.
- Bromberg et al 1978 : Production of jets and single particles at high p_T in 200 GeV hadron-beryllium collisions.
- Bromberg et al 1979a : Jets produced in π^- , π^+ and proton interactions at 200 GeV on hydrogen and aluminium targets.
- Bromberg et al 1979b : Production and correlations of charged particles with high p_T in 200 GeV/c $\pi^\pm p$, $K^- p$ and pp collisions.
- Bromberg et al 1979c : Experimental tests of quantum chromodynamics in high p_T jet production in 200 GeV/c hadron-proton collisions.
- CERN (C)
- Darriulat et al 1976a : Large transverse momentum photons from high energy proton-proton collisions.
- Darriulat et al 1976b : Structure of final states with a high transverse momentum π^0 in p-p collisions.
- CERN - College de France - Heidelberg - Karlsruhe (CCHK)
- Cottrell et al 1975 : Measurement of large transverse momentum positive particles produced at medium angles at $\sqrt{s} = 52.5$ GeV.
- Della Negra et al 1975a : Observation of leading particles in p-p interactions with large transverse momentum secondaries.
- Della Negra et al 1975b : Composition of particles emitted at large p_T and medium angles in pp collisions at $\sqrt{s} = 52.5$ GeV.
- Della Negra et al 1976 : Study of events with a positive particle of large transverse momentum emitted near the forward direction in p-p collisions at $\sqrt{s} = 52.5$ GeV.
- Della Negra et al 1977 : Observation of jet structure in high p_T events at the ISR and the importance of parton transverse momentum.

Drijard et al 1979 : Quantum number effects in events with a charged particle of large transverse momentum.

(I) Leading particles in single and diquark jets.

Drijard et al 1980 : ibid.

(II) Charge correlations in jets.

- CERN - Columbia - Oxford - Rockefeller (CCOR)

Angelis et al 1978 : A measurement of inclusive π^0 production at large p_T from p-p collisions at the CERN ISR.

Angelis et al 1979 : A study of final states containing high p_T π^0 's at the CERN ISR.

- CERN - Columbia - Rockefeller (CCR)

Büsser et al 1973 : Observation of π^0 mesons with large transverse momentum in high energy proton-proton collisions.

Büsser et al 1974a : Correlations between large transverse momentum π^0 mesons and charged particles at the CERN ISR.

Büsser et al 1974b : Correlation between two large transverse momentum π^0 mesons at the CERN ISR.

- CERN - Columbia - Rockefeller - Saclay (CCRS)

Büsser et al 1975 : A study of high transverse momentum η and π^0 mesons at the CERN ISR.

Büsser et al 1976 : A study of inclusive spectra and two-particle correlations at large transverse momentum.

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- CERN - Saclay (CS)

Clark et al 1978a : Inclusive π^0 production from high energy p-p collisions at very large transverse momentum.

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- Chicago - Princeton (CP)

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Antreasyan et al 1977a : Production of π^+ and π^- at large transverse momentum in p-p and p-d collisions at 200, 300 and 400 GeV.

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Antreasyan et al 1979 : Production of hadrons at large transverse momentum in 200, 300 and 400 GeV p-p and p-nucleus collisions.

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- Columbia - Fermilab - Stony Brook (CFS)

Kephart et al 1977 : Measurement of the dihadron mass continuum in p-Be collisions and a search for narrow resonances.

McCarthy et al 1978 : Nucleon number dependence of the production cross sections for massive dihadron states.

Fisk et al 1978 : Correlations between two hadrons at large transverse momenta.

Jöstlein et al 1979a : Scaling properties of high mass symmetric hadron - and pion-pair production in proton-beryllium collisions.

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Alper et al 1978 : Multiplicity distributions associated with charged hadron production over a range of transverse momentum and production angle at ISR energies.

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- Fermilab - Lehigh - Pennsylvania - Wisconsin (FLPW)

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FIGURE CAPTIONS

Figure 1 :

The naive parton model :

- a) the hard scattering (σ) between two incident partons factors out from the structure functions (F) and from the fragmentation functions (G).
- b) initial state : the partons taking part in the hard scattering have momenta decomposed as $x P_{inc}$ along the beam and k_T transversally. Scaling x distributions and strongly damped k_T 's are characteristic of the naive parton model.
- c) final state : the struck partons fragment into hadrons with momenta $z P_j$ along the parton momentum and q_T transversally. Scaling z distributions and strongly damped q_T 's are characteristic of the naive parton model.

The debris of the incident hadrons travel near the beam directions.

Figure 2 :

The pioneer data of the CERN - Columbia - Rockefeller Collaboration, first to extend the explored p_T scale up to 9 GeV/c, were presented at the 16th Int. Conf. on high Energy Physics (Chicago) in 1972. Invariant π^0 production cross-sections are displayed vs p_T for different values of \sqrt{s} in the ISR energy range. The measured points fall orders of magnitude above the extrapolation of low p_T data (solid line). The increase with \sqrt{s} is well described by a scaling form in $p_T^{-8.24}$.

Figure 3 :

Illustration of the dimensional counting rules for the inclusive cross section $a+b \rightarrow c+\dots$. Active quark lines (taking part in the hard scattering) are indicated as solid lines. Here, the hard scattering term is the constituent interchange term $q+m \rightarrow q+m$ with $n_a = 6$. Passive quark lines are indicated as dashed lines ; $n_p = 7$ in the example shown (5 from the initial state and 2 for fragmentation).

Figure 4 :

Phase space density of LPTH final states obtained from actual data of the BFS Collaboration. Particle densities are shown in the rapidity-azimuth space ; they are averaged over a large number of LPTH events and referred to "normal" events on which no special trigger requirement is imposed. The trigger jet is visible, despite the trigger-bias effect, in the vicinity of the trigger particle. The away side-jet is responsible for the broad enhancement at opposite azimuth (marked "away"). Owing to the averaging over several events, it spans a wide range of rapidity.

Figure 5 :

Recent ISR measurements of the inclusive π^0 production cross section, extending to $p_T = 16$ GeV/c, have been performed by three Collaborations. The discrepancy observed between the three measurements may be blamed on different calibrations of the p_T scale ; however the three experiments agree on the change of scaling behaviour towards larger p_T (see Figure 7).

Figure 6 :

A typical QCD calculation of inclusive π production, due to Contogouris, Gaskell and Papadopoulos (1978). The effects of the q-q, q-g and g-g terms are shown separately on the lower plot ; that of constituent internal transverse momentum, k_T , is illustrated for $\langle k_T \rangle = 0$ and 0.5 GeV/c. Gluon distributions are taken of the form $(1-x)^Y$.

Figure 7 :

The effective scaling parameter $n(x_T, s)$ has been evaluated by the CCOR Collaboration from their π^0 production data. It decreases when x_T and/or s increase and it approaches 4, the quark-quark term value, at large x_T and s .

Figure 8 :

Chicago-Princeton data on the ratio between π^- and π^+ production in $\pi^- p$ collisions. The data rule out any significant constituent interchange contribution but support QCD expectations (model predictions as quoted by Jacob (1979) in his recent review).

Figure 9 :

The γ/π^0 ratio as measured by the ABCS Collaboration at three ISR energies : a) $\sqrt{s} = 30.6$ GeV, b) $\sqrt{s} = 53.1$ GeV, c) $\sqrt{s} = 62.4$ GeV. The curves are QCD predictions (Halzen and Scott 1978 a and b).

Figure 10 :

Azimuthal correlation between two large transverse momentum π^0 's produced at the ISR, as measured by the ABCS Collaboration. Distributions in ϕ , the azimuthal opening of the pair, are shown for three intervals of the total transverse energy E_T (evaluated from the missing transverse momentum to the π^0 pair). A clear back to back structure emerges as soon as E_T exceeds ~ 10 GeV.

Figure 11 :

The structure of LPTH events in three different azimuthal wedges separated by $\Delta\phi$ from the large transverse momentum π^0 trigger, as studied by the CS Collaboration at the ISR. The data are normalized to "normal" collisions. The multiplicity (N) and transverse momentum (p_T) distributions out of the trigger plane are not affected. The trigger jet multiplicity is depressed relatively to that of the away-jet by the trigger bias effect.

Figure 12 :

Data obtained by the CCOR Collaboration in the study of charged particles associated with a π^0 having more than 7 GeV/c transverse momentum and produced in the opposite azimuthal hemisphere.

a) Rapidity distributions are referred to the π^0 rapidity. The away-jet structure is washed out by the wide rapidity span of the away jet.

b) Rapidity distributions are referred to the rapidity of the hardest away particle (leader). The away-jet structure is now clearly evidenced, the collimation increasing with the transverse momentum p_T of the charged particle.

Figure 13 :

The inclusive jet production cross section, as measured by the CLFCI Collaboration, is compared to inclusive single π production. The solid lines correspond to two different QCD predictions (quoted by Jacob (1979) in his recent review).

Figure 14 :

The mean charged multiplicity of hadron jets as measured in LPTH data (BS : open circles, CS : full circles), in neutrino-proton interactions (full triangles, Van der Velde 1979), in e^+e^- annihilations at Spear, Doris (cross hatched zones) and at PETRA (open triangles, Wolf 1979).

All data are referred to the equivalent e^+e^- energy.

Figure 15 :

Total transverse momentum of charged secondaries in trigger jets with an identified single particle trigger of transverse momentum p_T (Data from the BFS Collaboration).

Figure 16 :

The mean transverse momentum distribution of jet fragments with respect to the jet axis as measured by the CCOR Collaboration for different values of the trigger transverse momentum.

Figure 17 :

Transverse momentum distribution of charged (on the left) and neutral (on the right) jet fragments with respect to the jet axis (CS Collaboration). Rather than q_T it is its component on the plane of the beams, \tilde{q}_T , which is measured. Solid lines correspond to Gaussian distributions corrected for detector acceptance and having $\langle \tilde{q}_T^2 \rangle^{1/2} =$ a) 0.3, b) 0.45 and c) 0.60 GeV/c.

Using the CCOR result on the isotropy of the jet fragmentation around its axis these data correspond to $\langle q_T \rangle \approx 0.55$ GeV/c.

Figure 18 :

The mean transverse momentum of jet fragments with respect to the jet axis. All data are referred to the equivalent e^+e^- energy $\sqrt{s^{ee}}$. LPTH data ($p_T > 800$ MeV/c) are shown as black circles (CS). The e^+e^- data (crosses) and neutrino data (open triangles) are for all fragments. Selecting the harder fragments (Scott 1978) brings the neutrino data (full triangles) in agreement with LPTH data. Similarly, for e^+e^- data measured at PETRA (Söding 1979), the selection $z > 0.2$ causes $\langle q_T \rangle$ to increase to about 0.45 GeV/c at $\sqrt{s} \approx 17$ GeV.

Figure 19 :

The slopes b obtained from exponential fits to the jet fragmentation function in the interval $0.2 < z < 0.8$ in e^+e^- annihilation (full circles) and LPTH data of the BS Collaboration (open circles).

Figure 20 :

Normalized z distributions measured by the ABCS Collaboration and evidencing the scaling behaviour of the fragmentation function : the fractionnal contribution of given z intervals is independent of the trigger momentum.

Figure 21 :

Jet fragmentation functions measured in different processes :

$U-p$ interactions (open triangles) Van der Velde 1979

e^+e^- annihilations (solid line) Hanson et al 1975

pp collisions (full circles) CS, $p_T < 6$ GeV/c

(open circles) CS, $p_T > 6$ GeV/c

(full squares) CCOR, $p_T > 5$ GeV/c

(open squares) CCOR, $p_T > 7$ GeV/c.

Figure 22 :

Fermilab data on jet production at 90° . The ratio of the cross sections $p+p \rightarrow \text{jet} + \dots$ to $\pi+p \rightarrow \text{jet} + \dots$ is displayed versus the jet transverse momentum, evidencing the increased pion efficiency at larger values of p_T .

Figure 23 :

The transverse momentum imbalance between two 90° jets produced in $p-p$ collisions (FLPW). Similar data have been obtained by the CS Collaboration at the ISR. The observed width corresponds to an effective k_T with a mean value of about 1 GeV/c.

Figure 24 :

The dependence of $\langle p_{out} \rangle$ upon x_e as measured by the CCOR Collaboration for different values of the trigger transverse momentum p_T .

Figure 25 :

Invariant cross-sections for the production of large mass pion pairs :

a) $\pi^+\pi^-$ from the CFS Collaboration

b) $\pi^0\pi^0$ from the CCOR Collaboration.

The solid lines are the results of a QCD calculation by Baier, Engels and Petersson (1979). The contributions of various terms are indicated

in a) : $q+q \rightarrow q+q$ (----),

$q+g \rightarrow q+g$ (-.-.-),

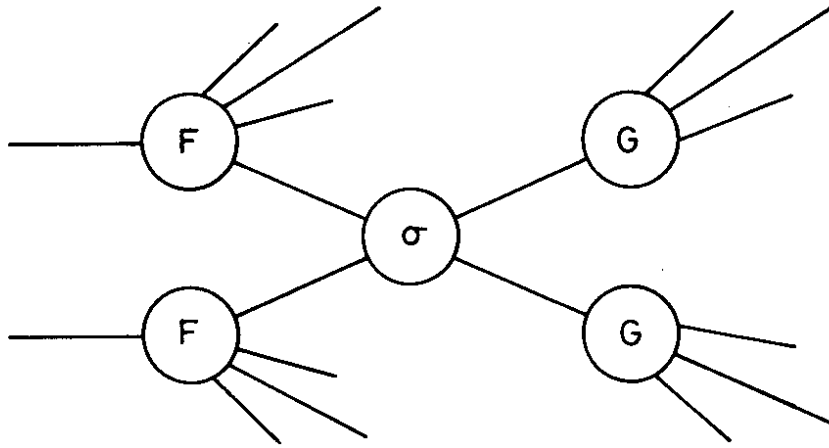
$g+g \rightarrow g+g$ (.....),

and $g+g \rightarrow q+\bar{q}$ (-....-....-).

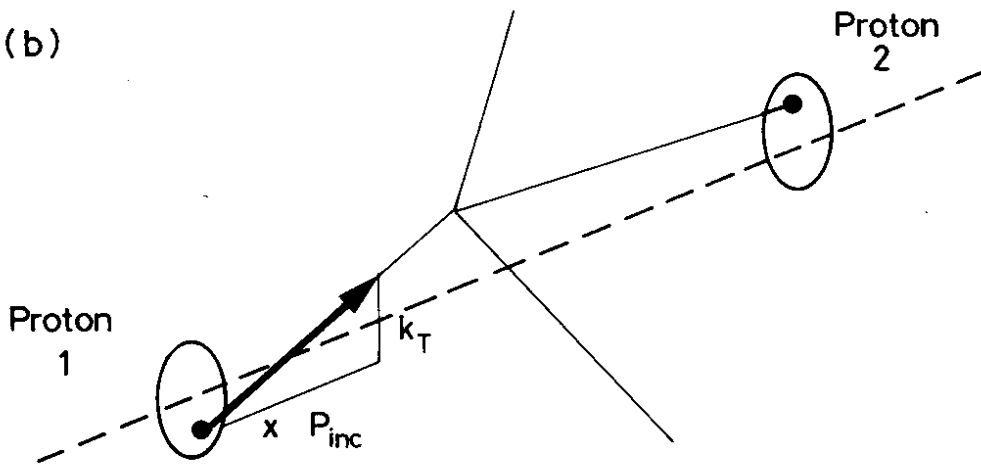
Figure 26 :

Anticipated jet yields in $p\bar{p}$ collisions at ISR, $\sqrt{s} = 62$ GeV, and at the collider, $\sqrt{s} = 540$ GeV as calculated in the QCD leading log approximation by Horgan (quoted by Jacob 1979).

(a)



(b)



(c)

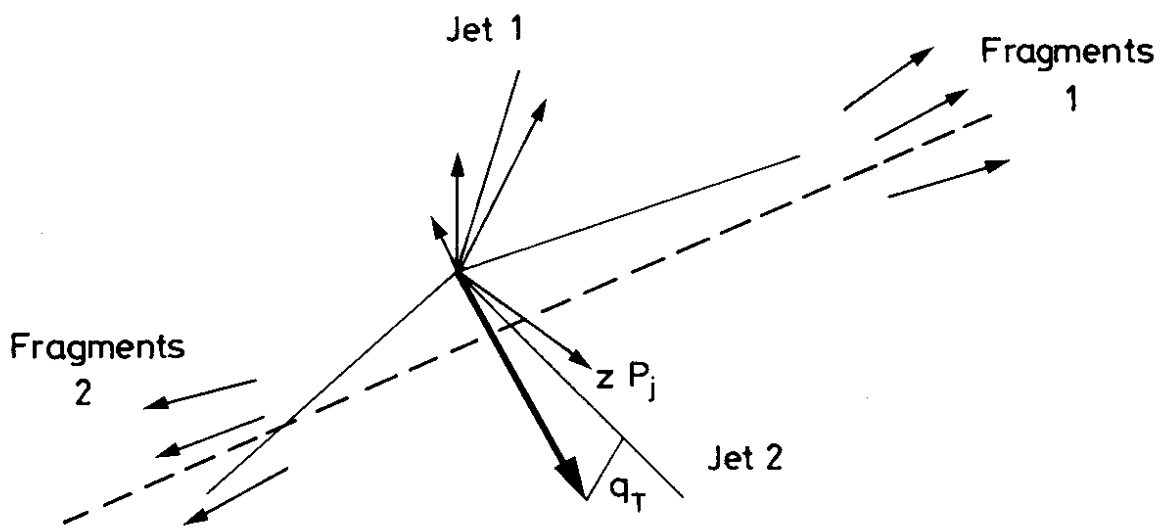


Fig. 1

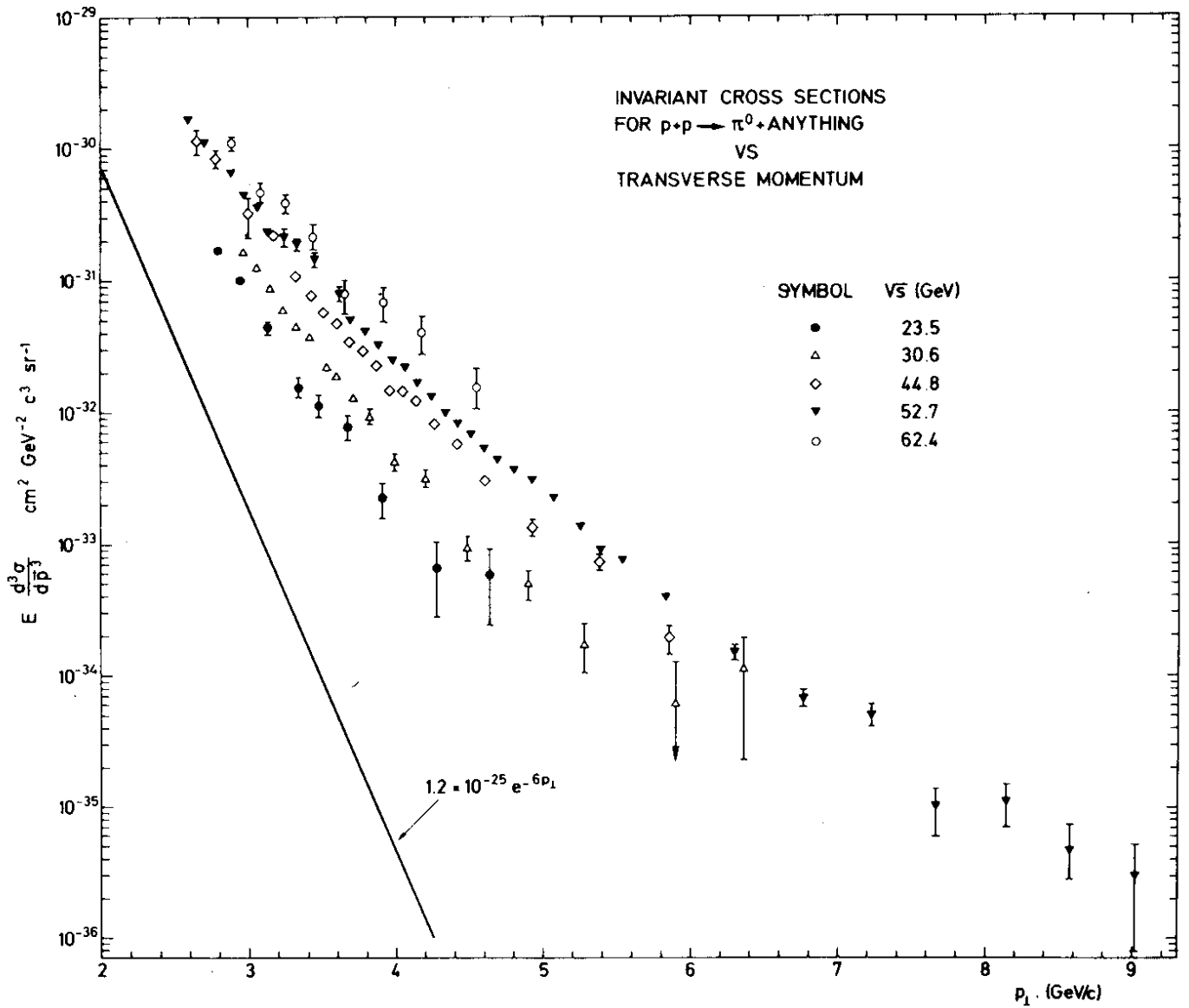


Fig. 2

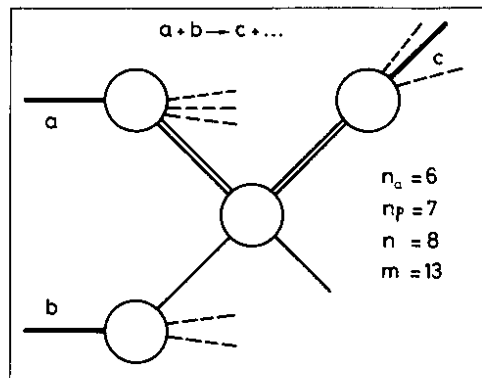


Fig. 3

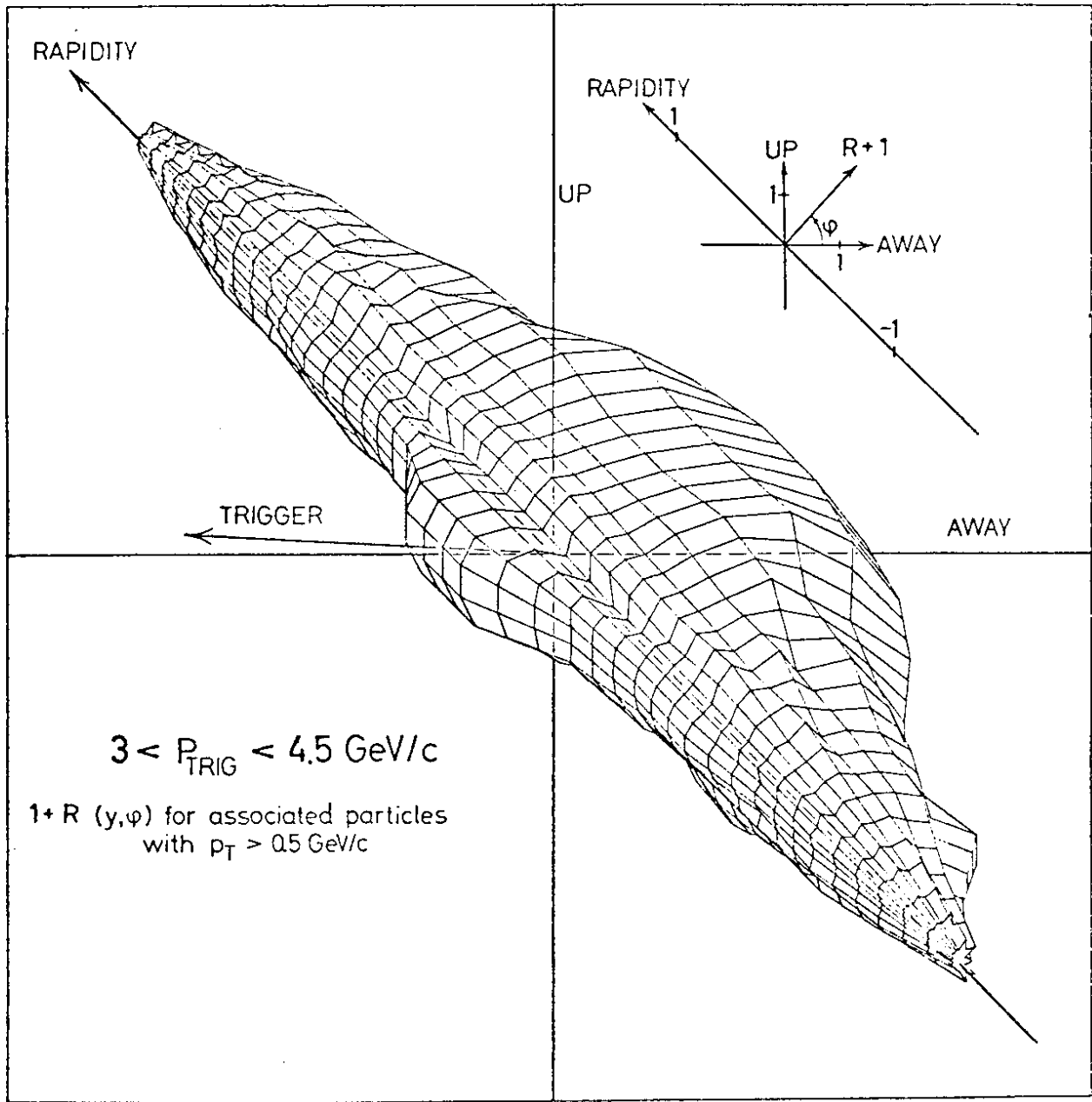


Fig. 4

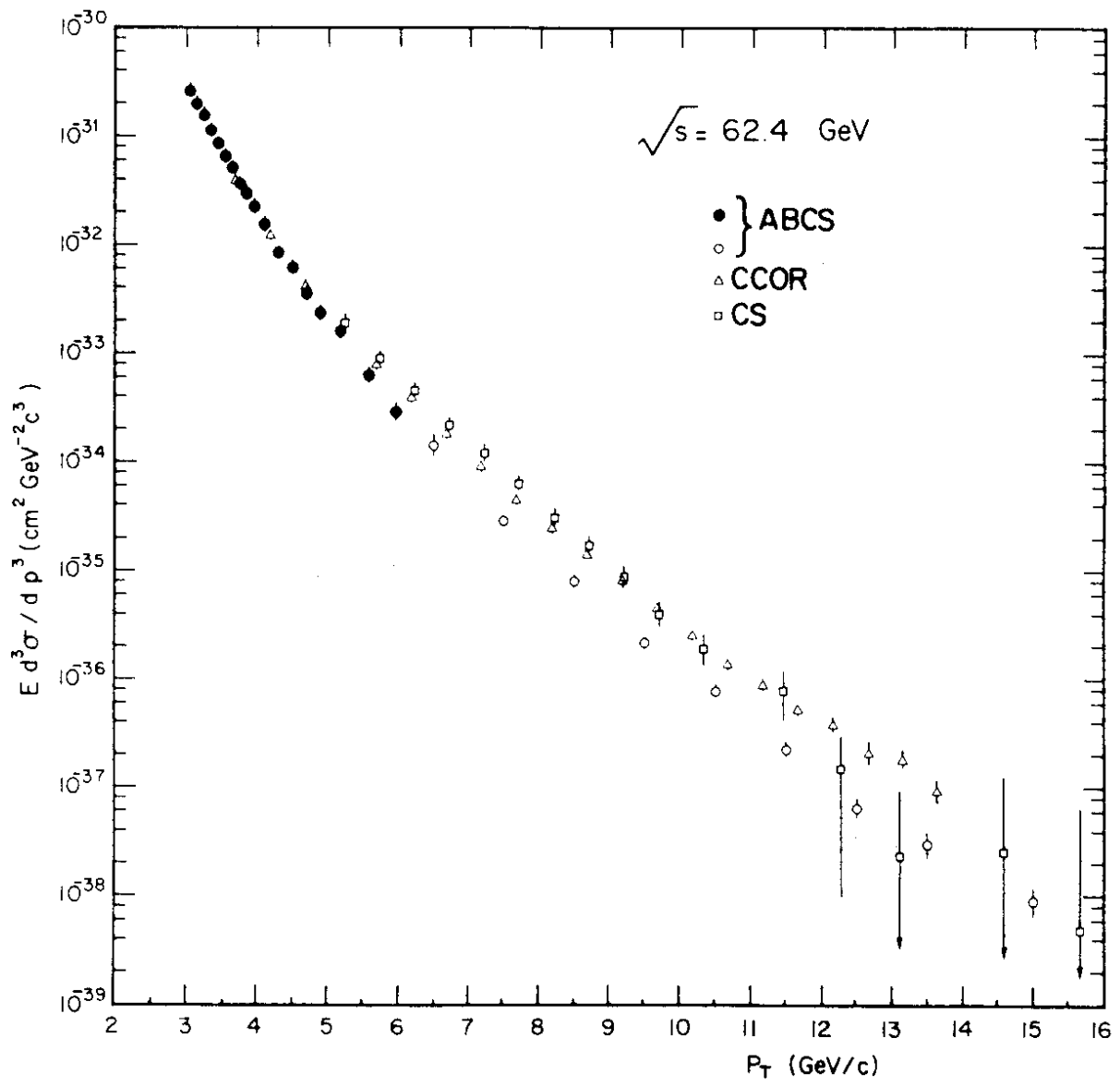


Fig. 5

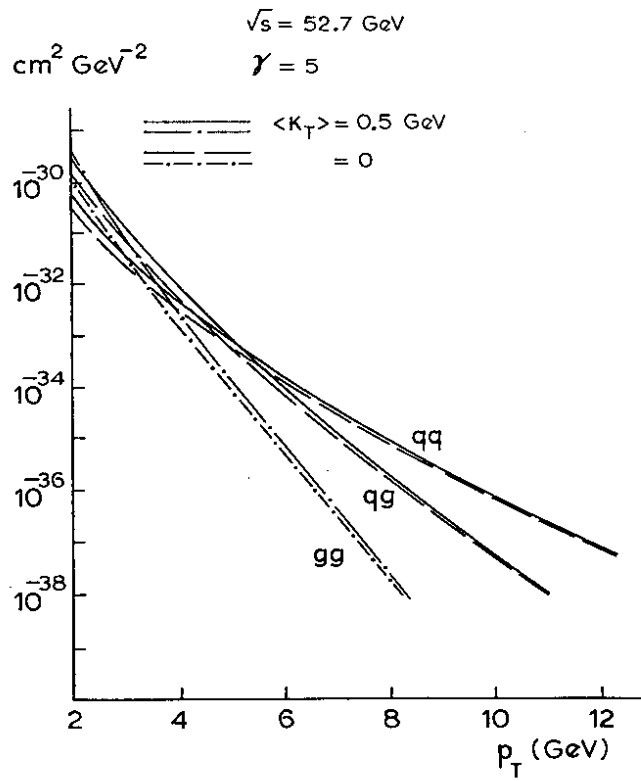
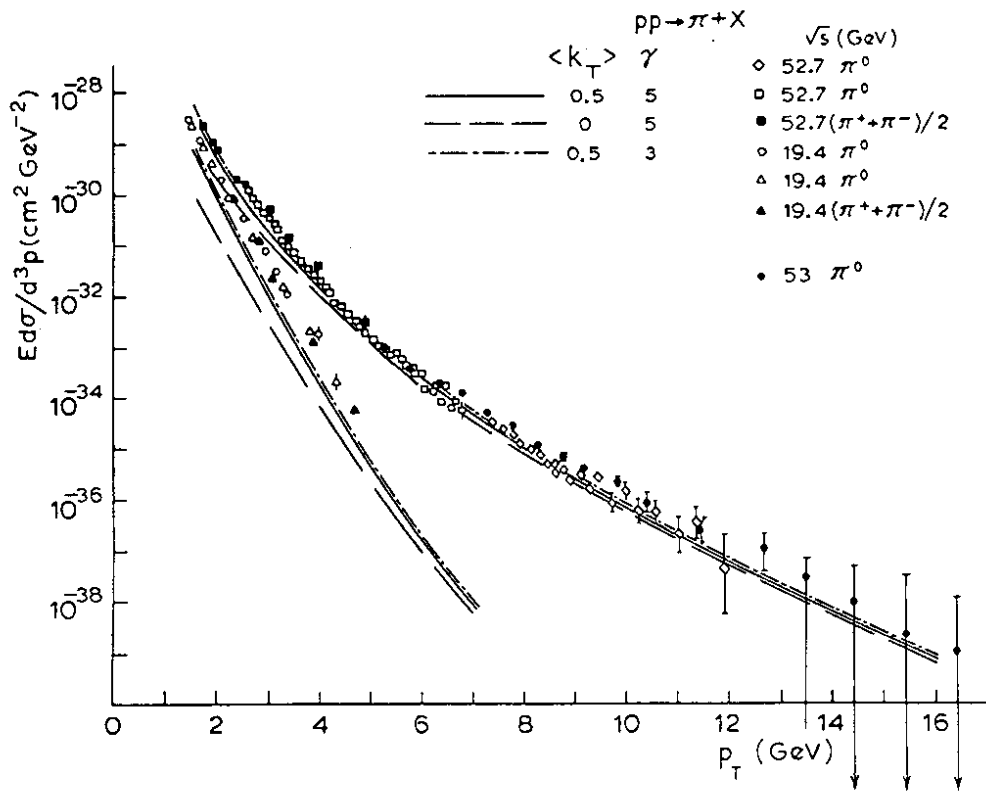
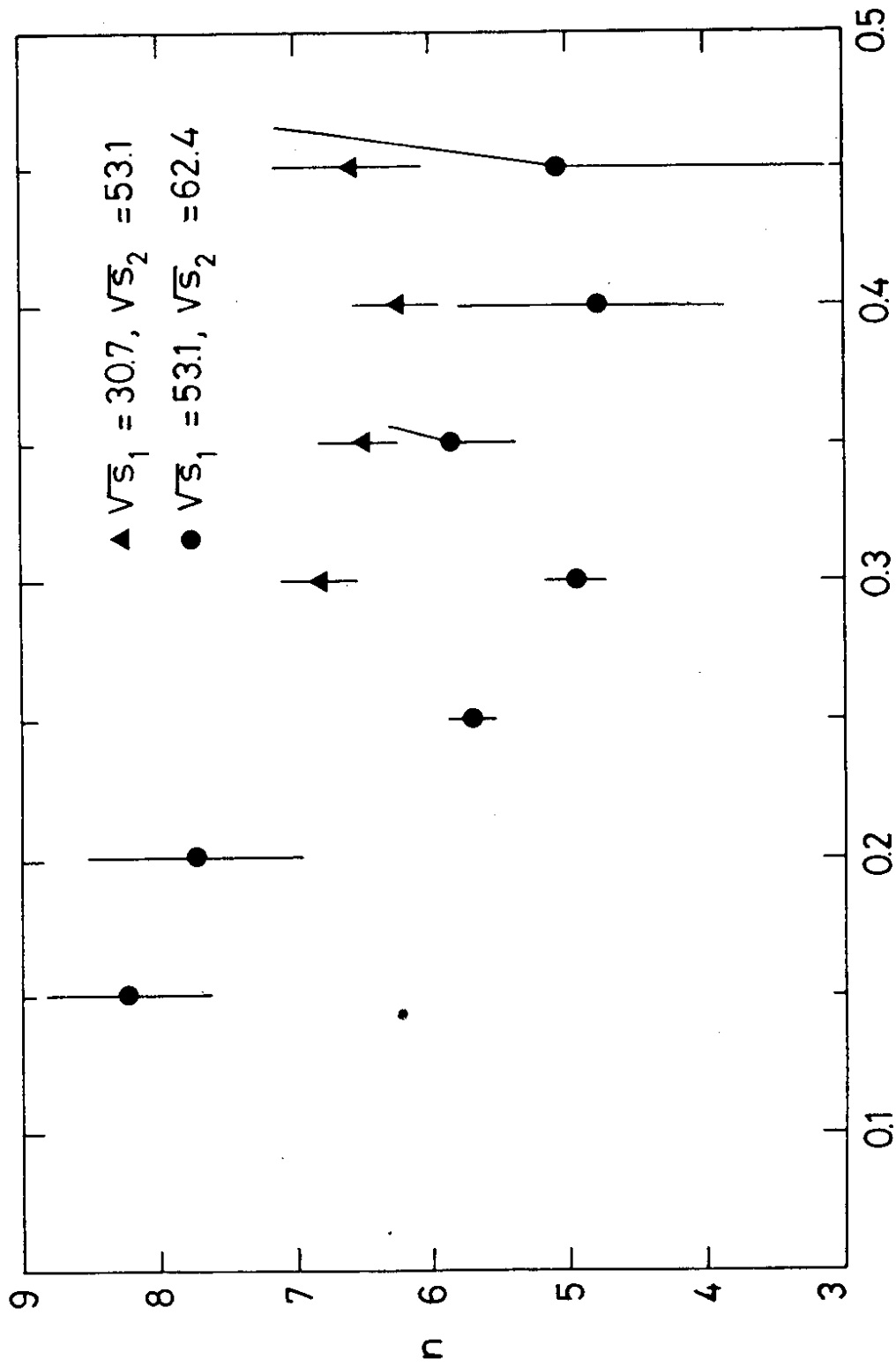


Fig. 6



x_T
Fig. 7

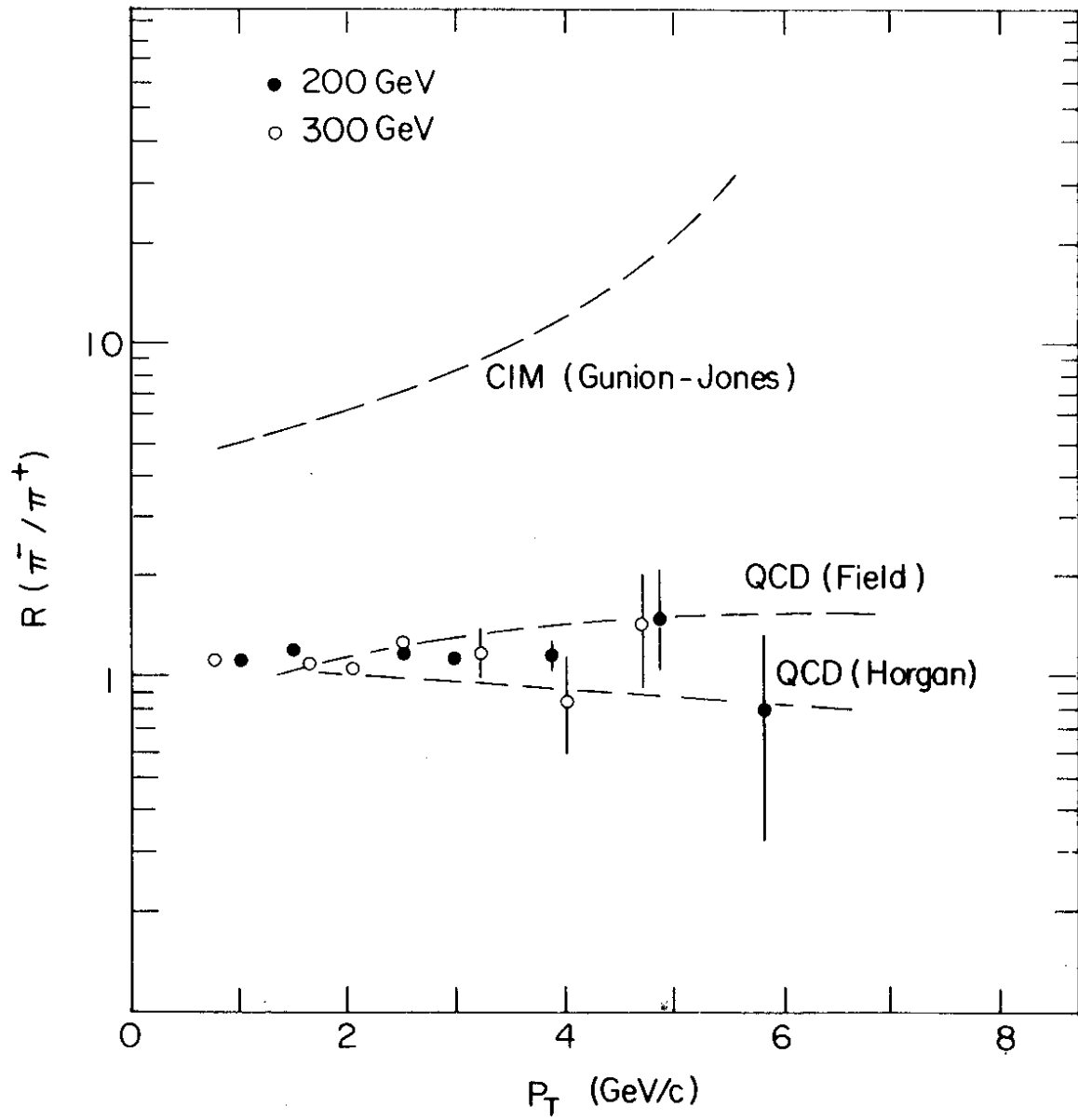


Fig. 8

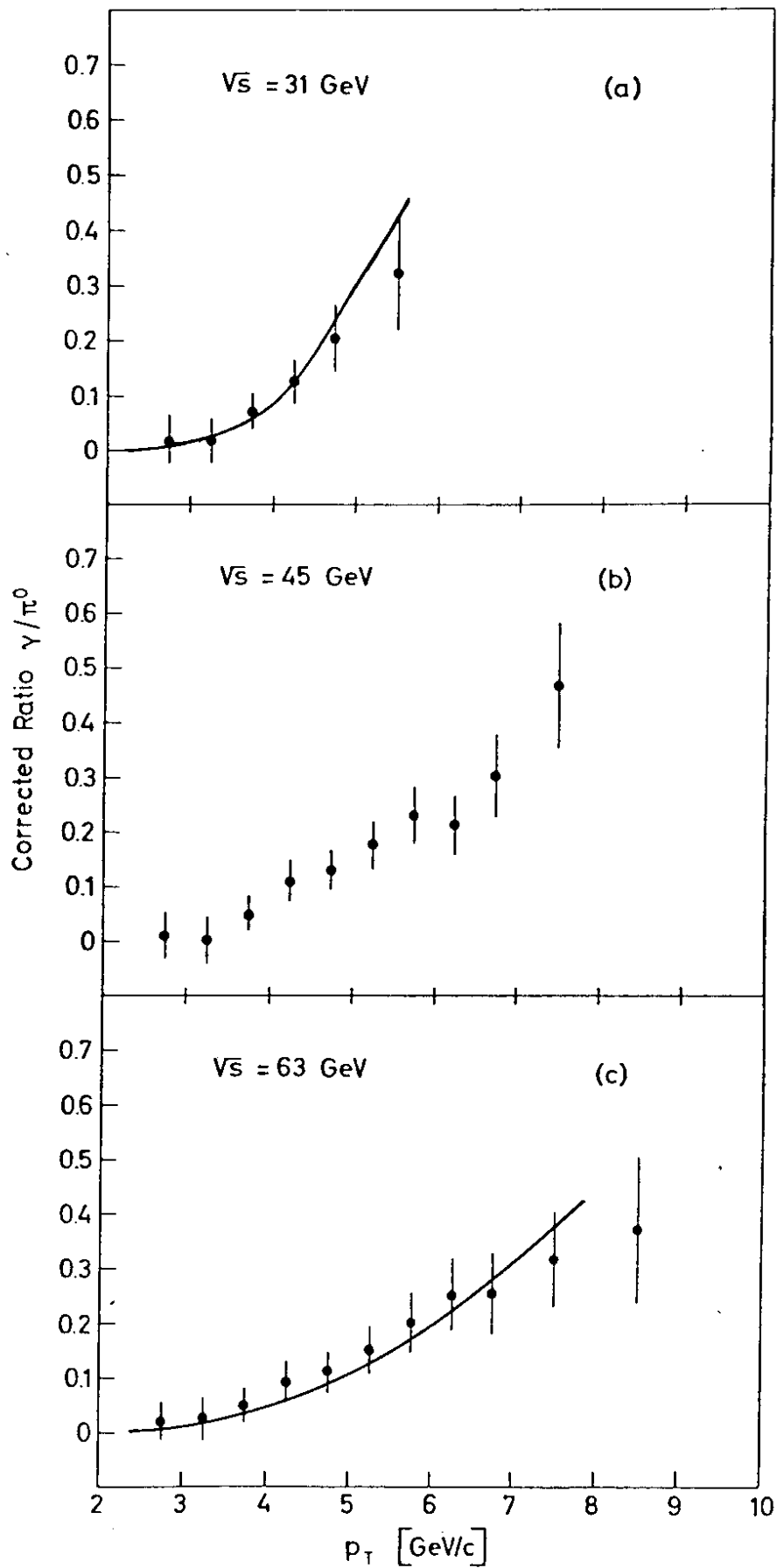


Fig. 9

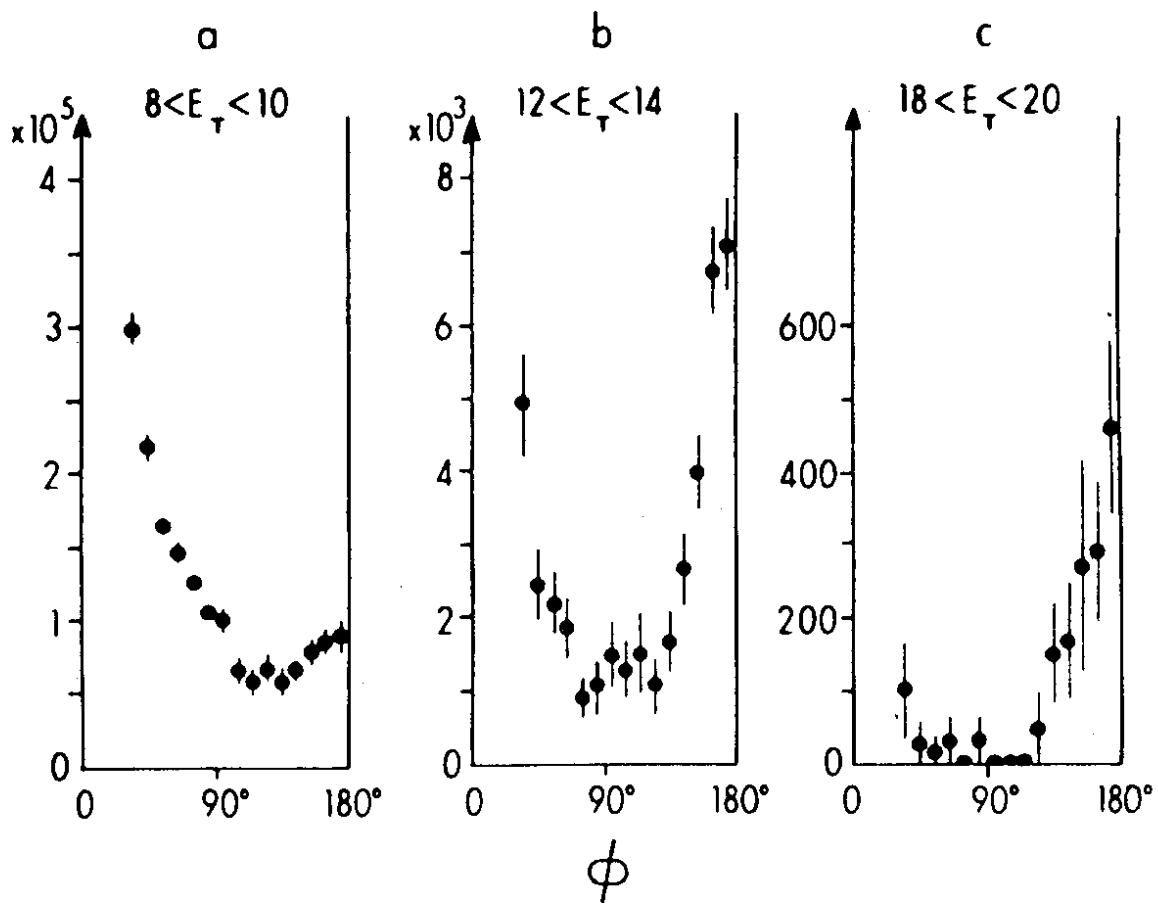


Fig. 10

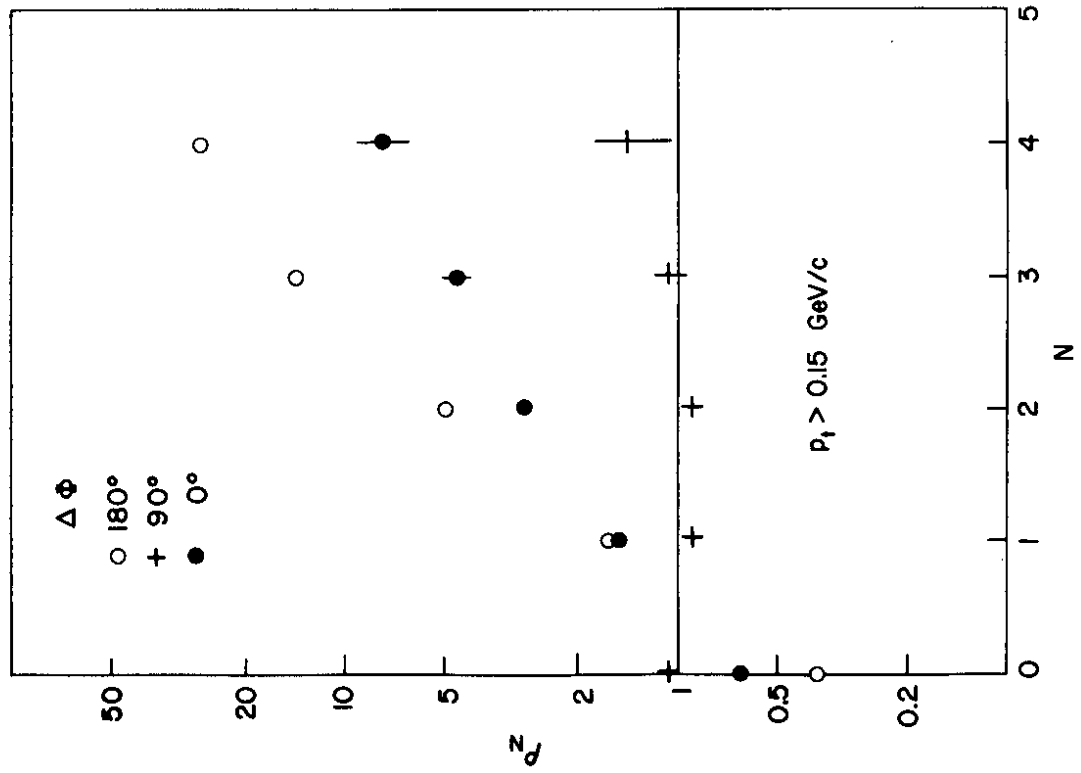
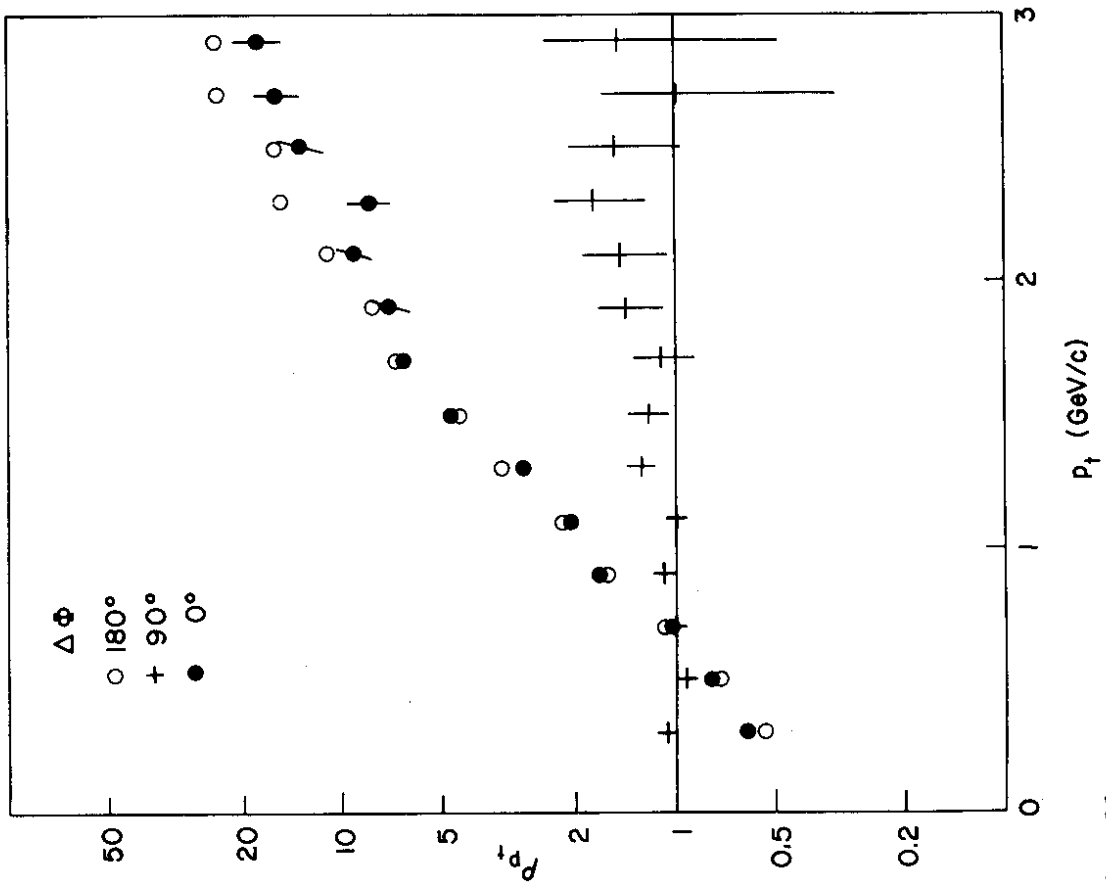


Fig. 11

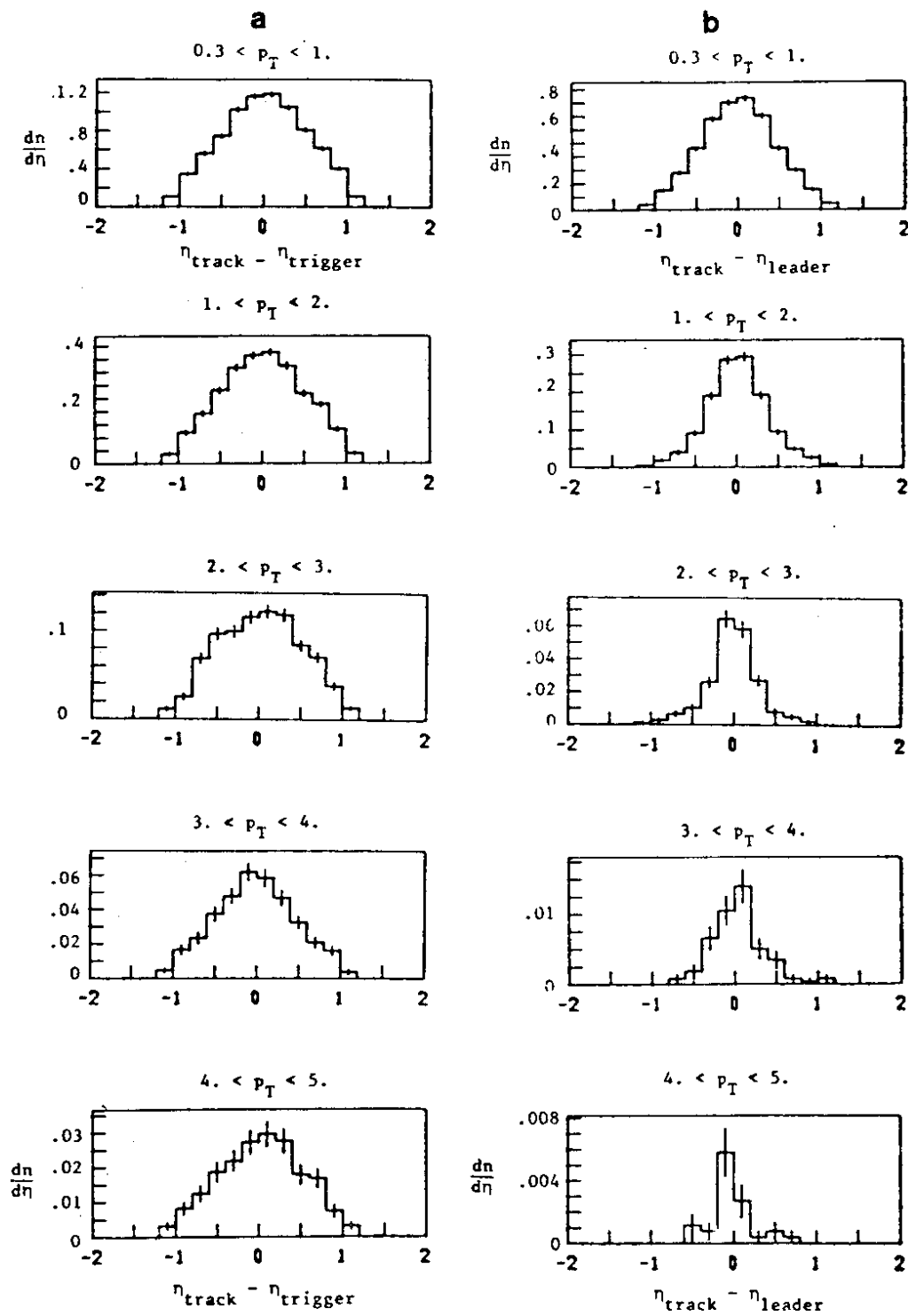


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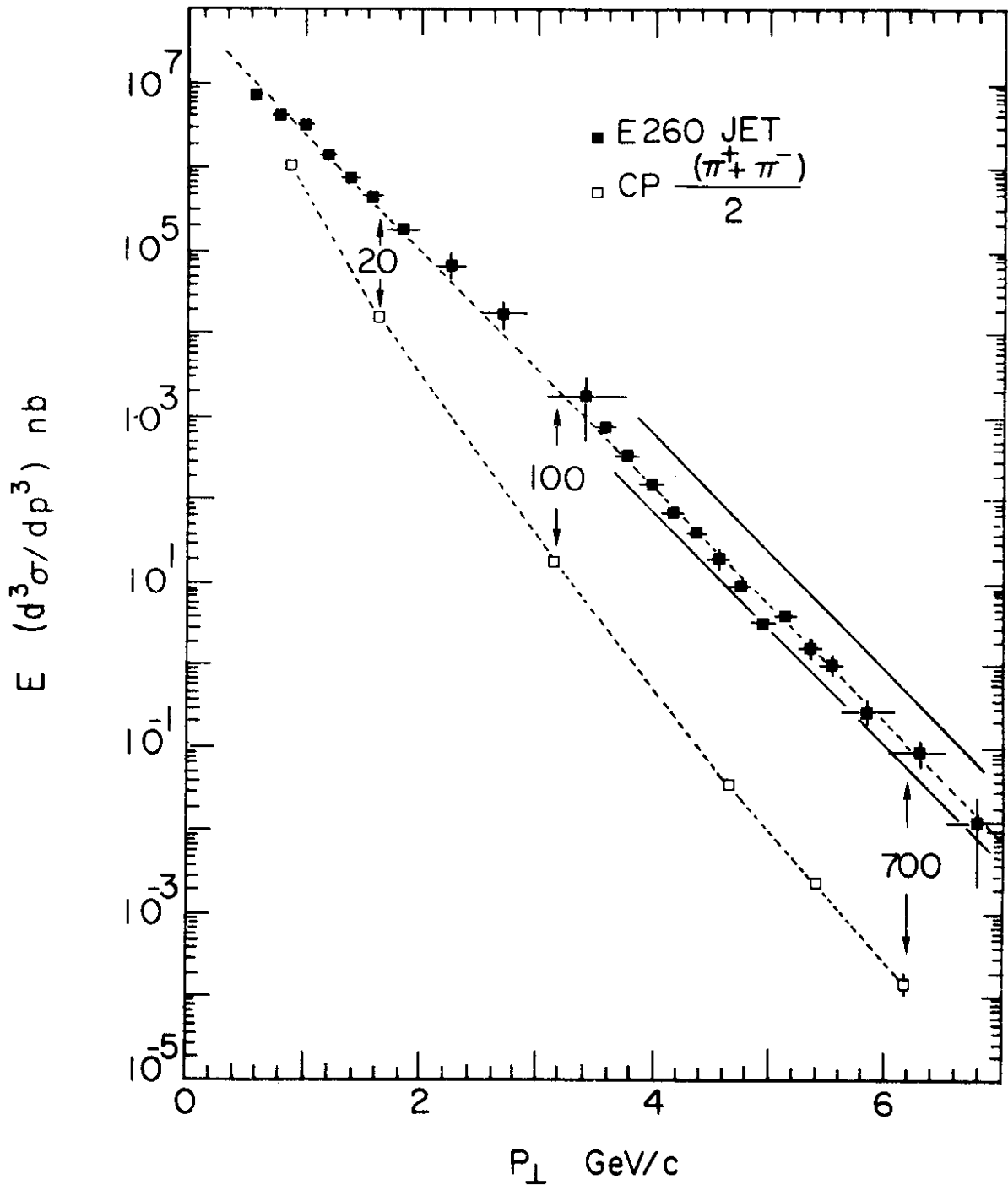


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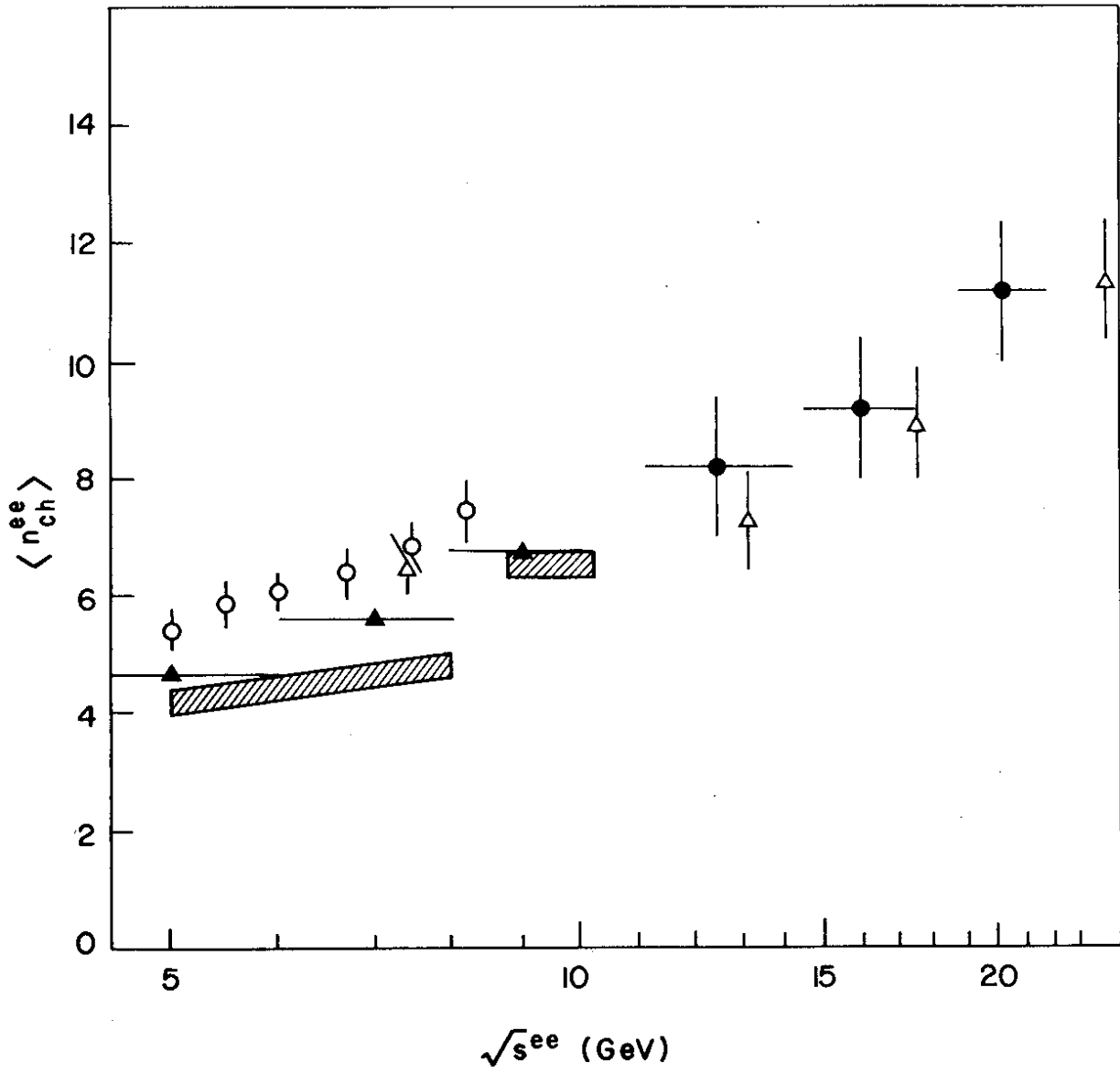


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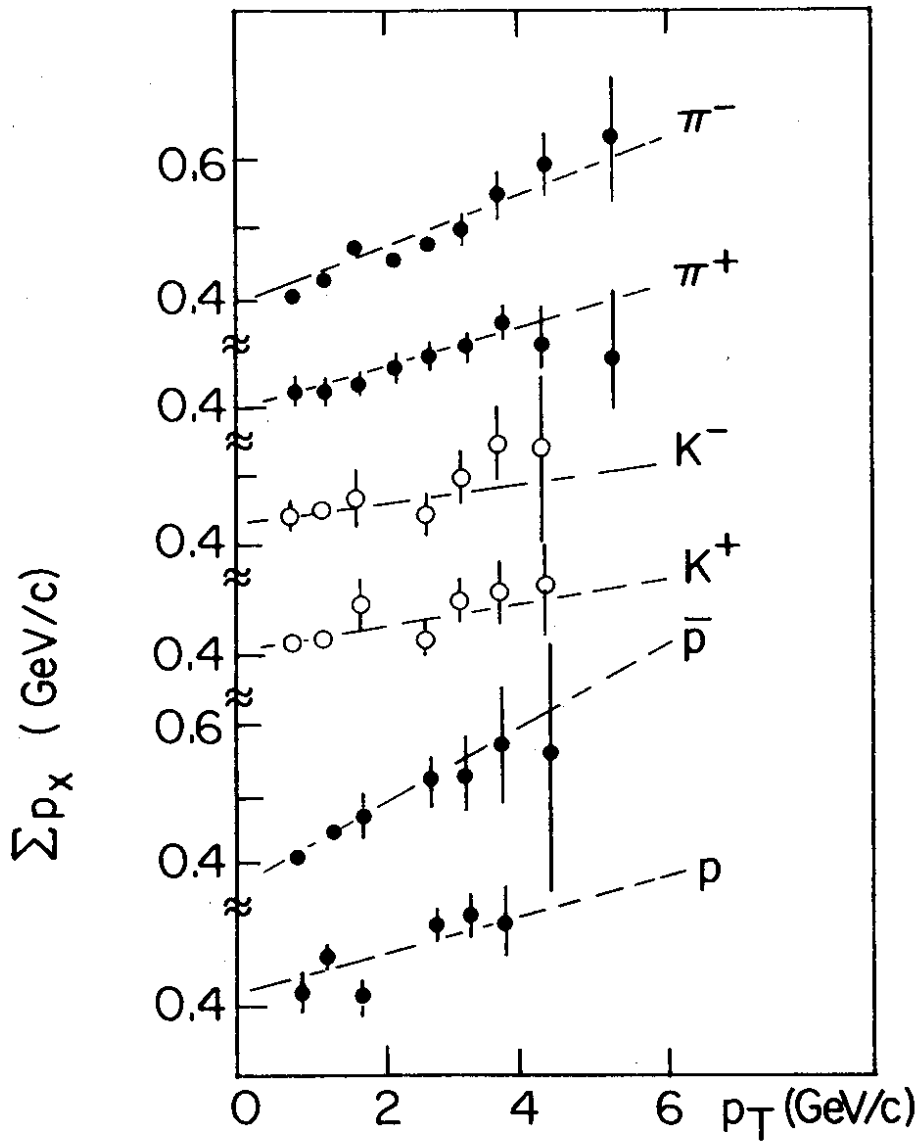


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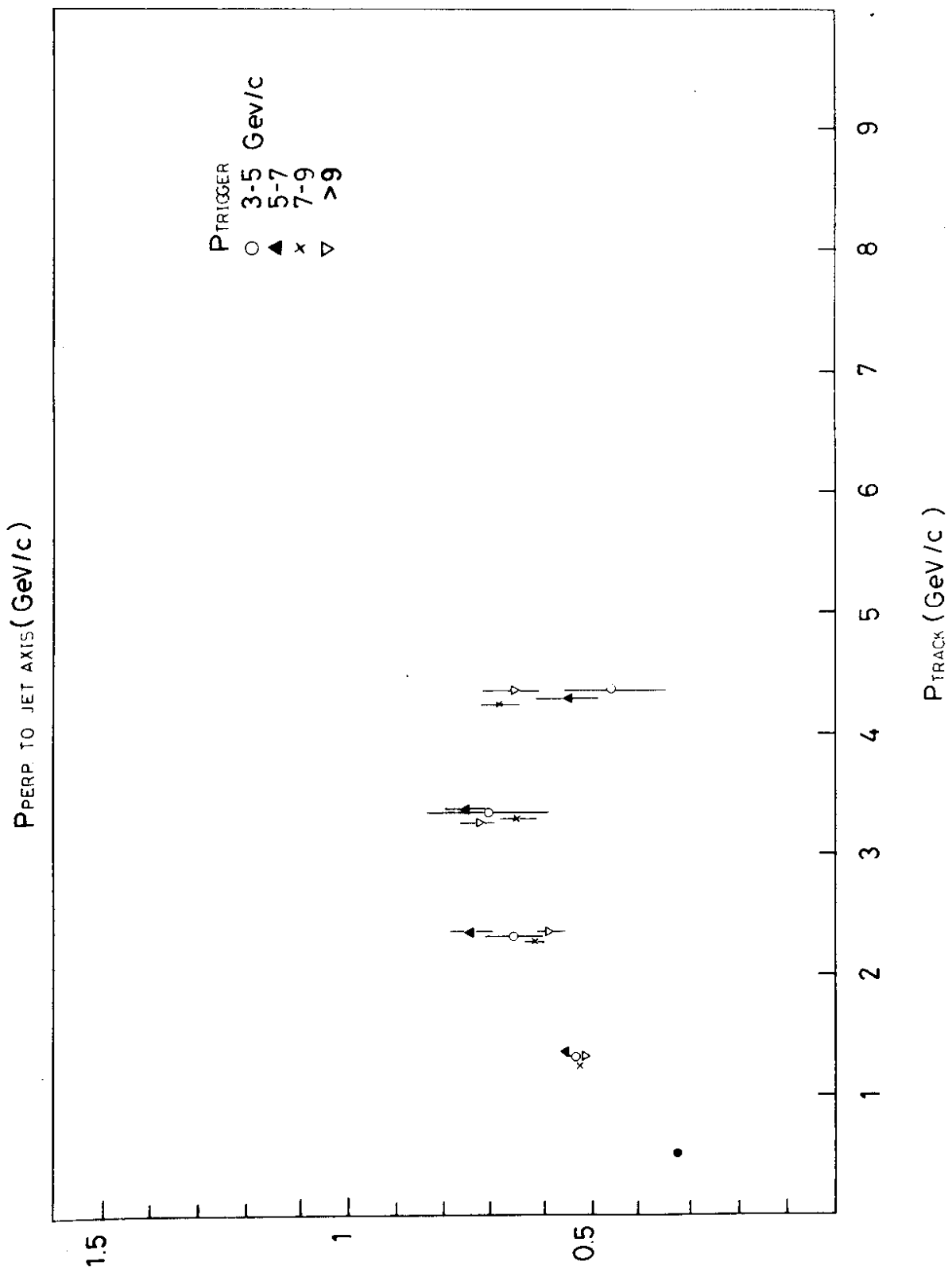


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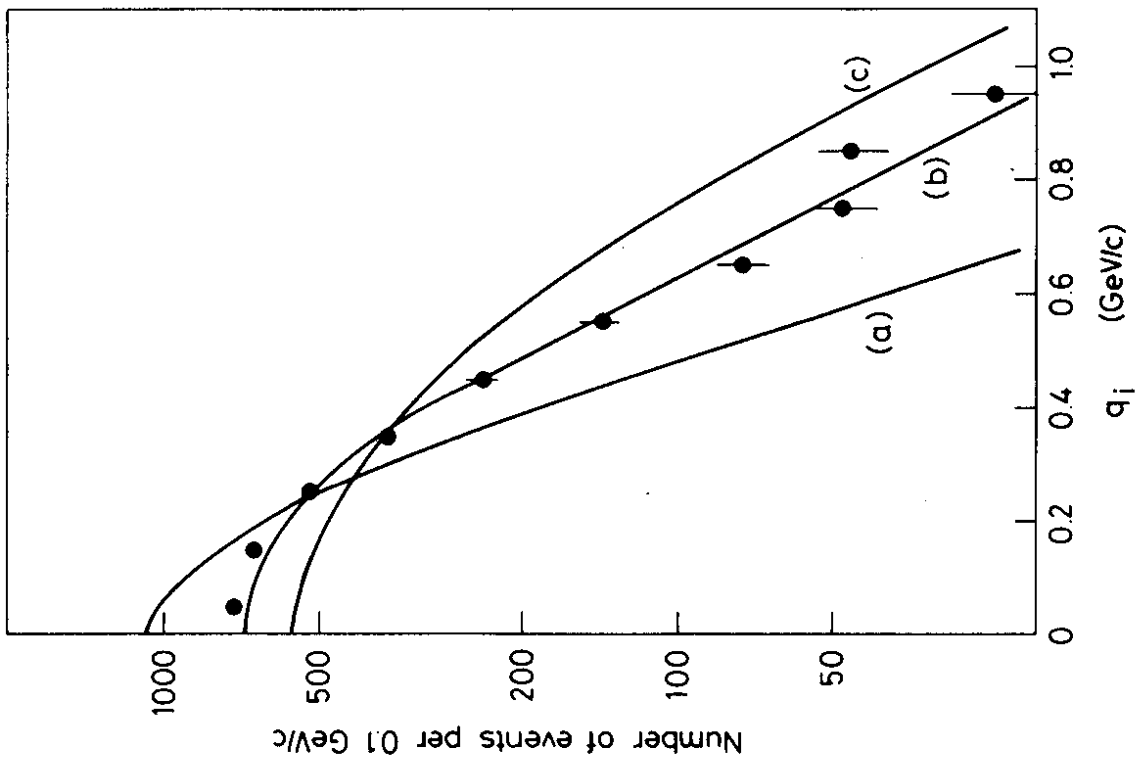
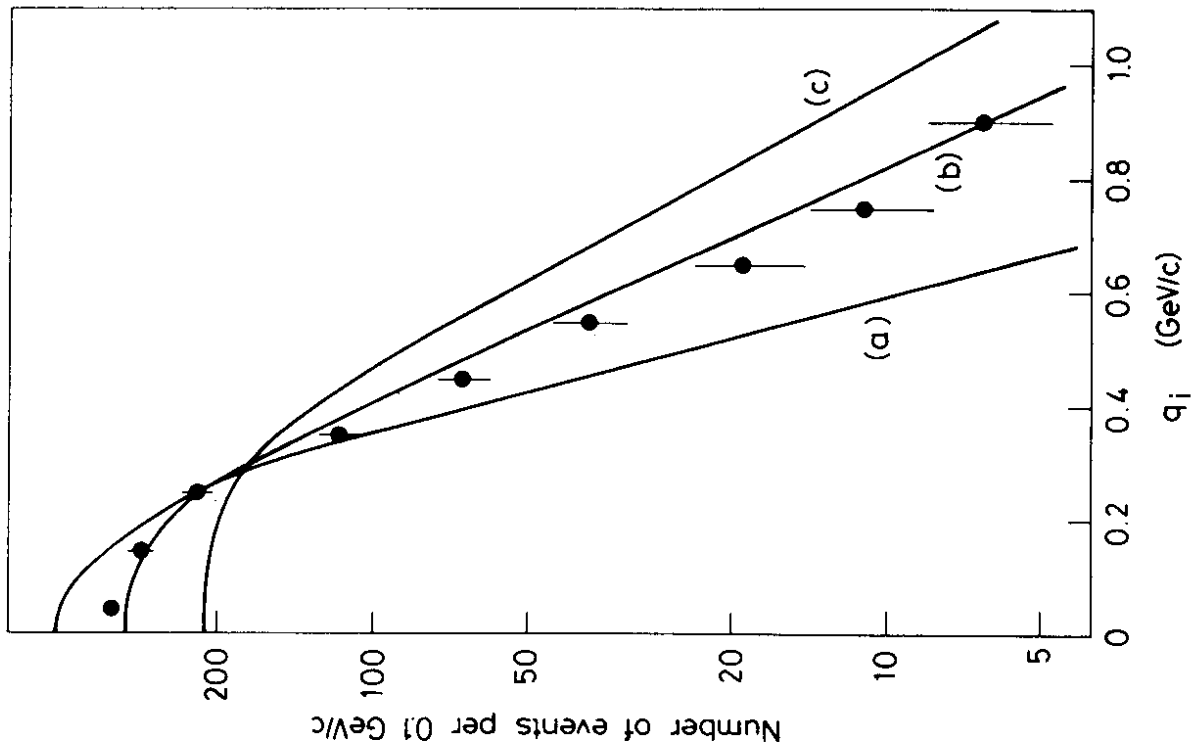


Fig. 17

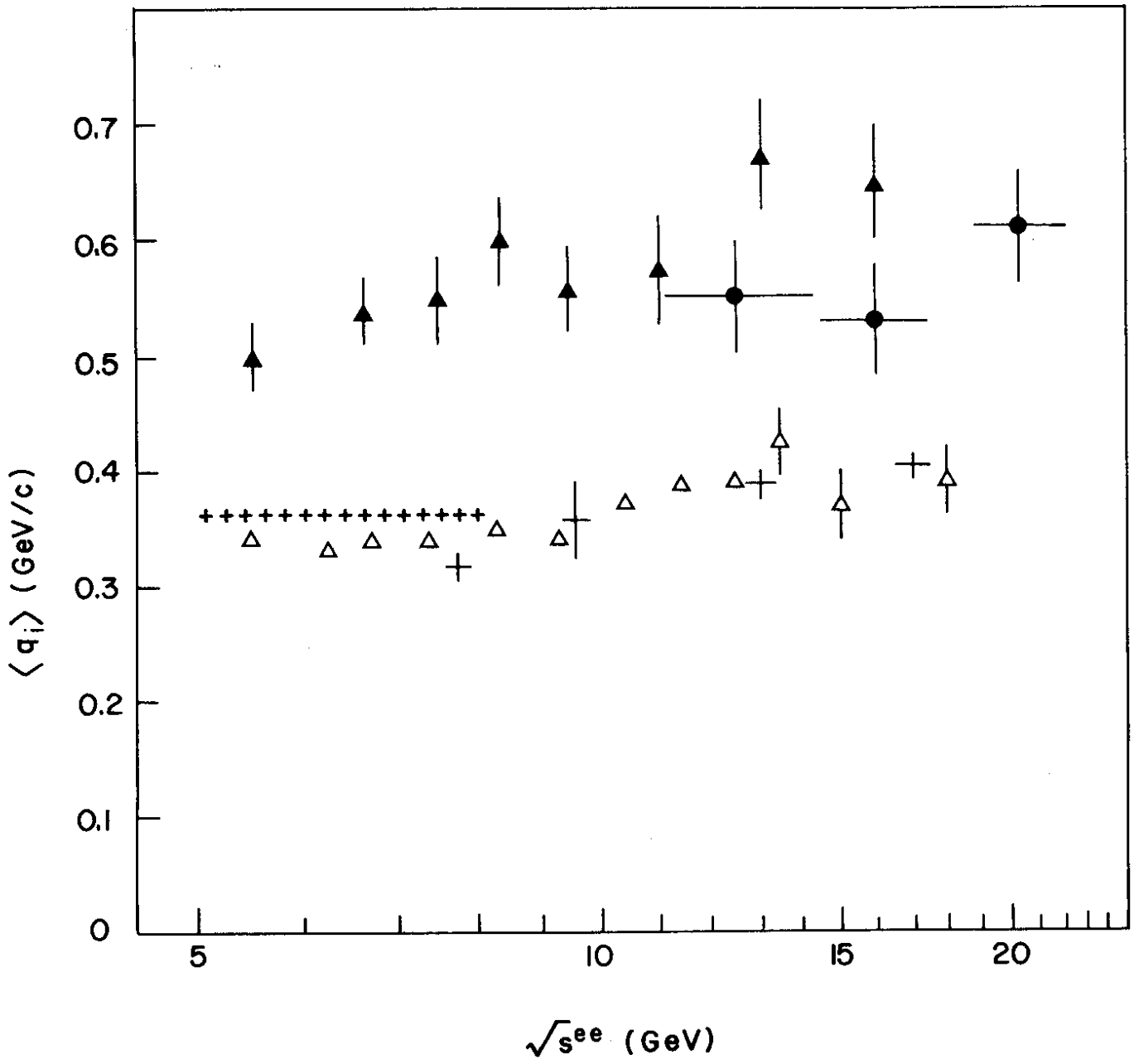


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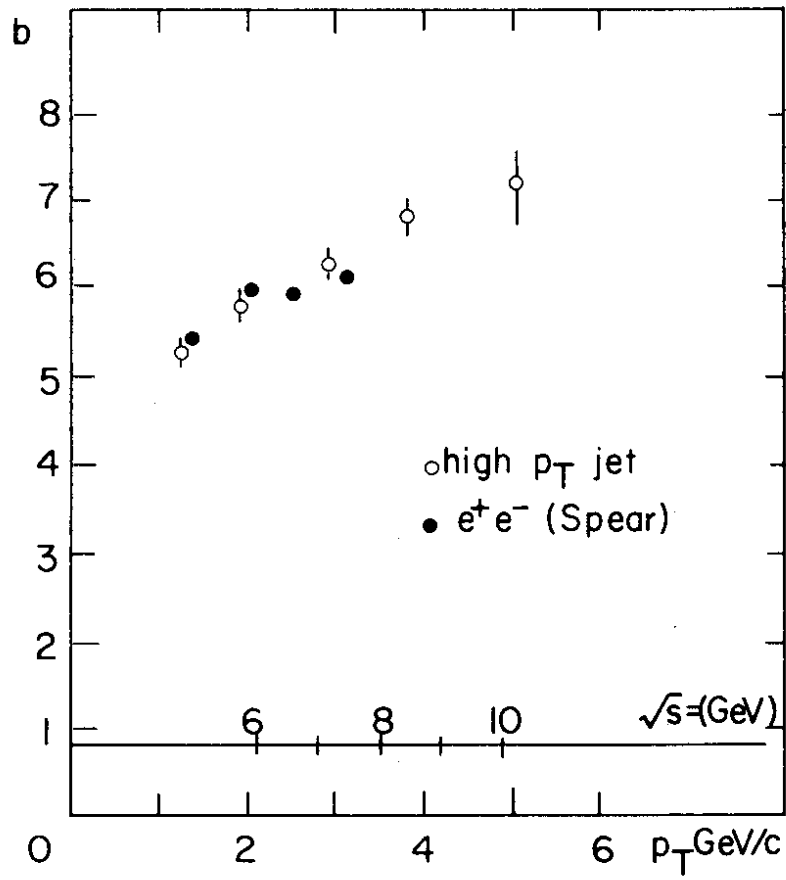


Fig. 19

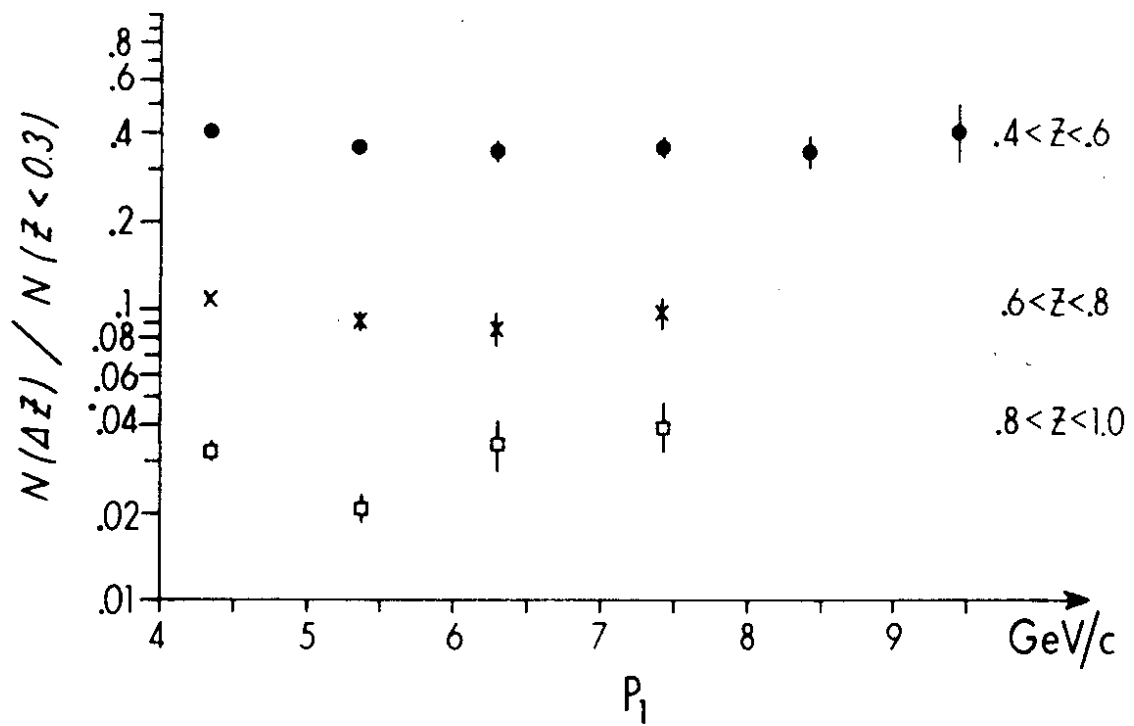


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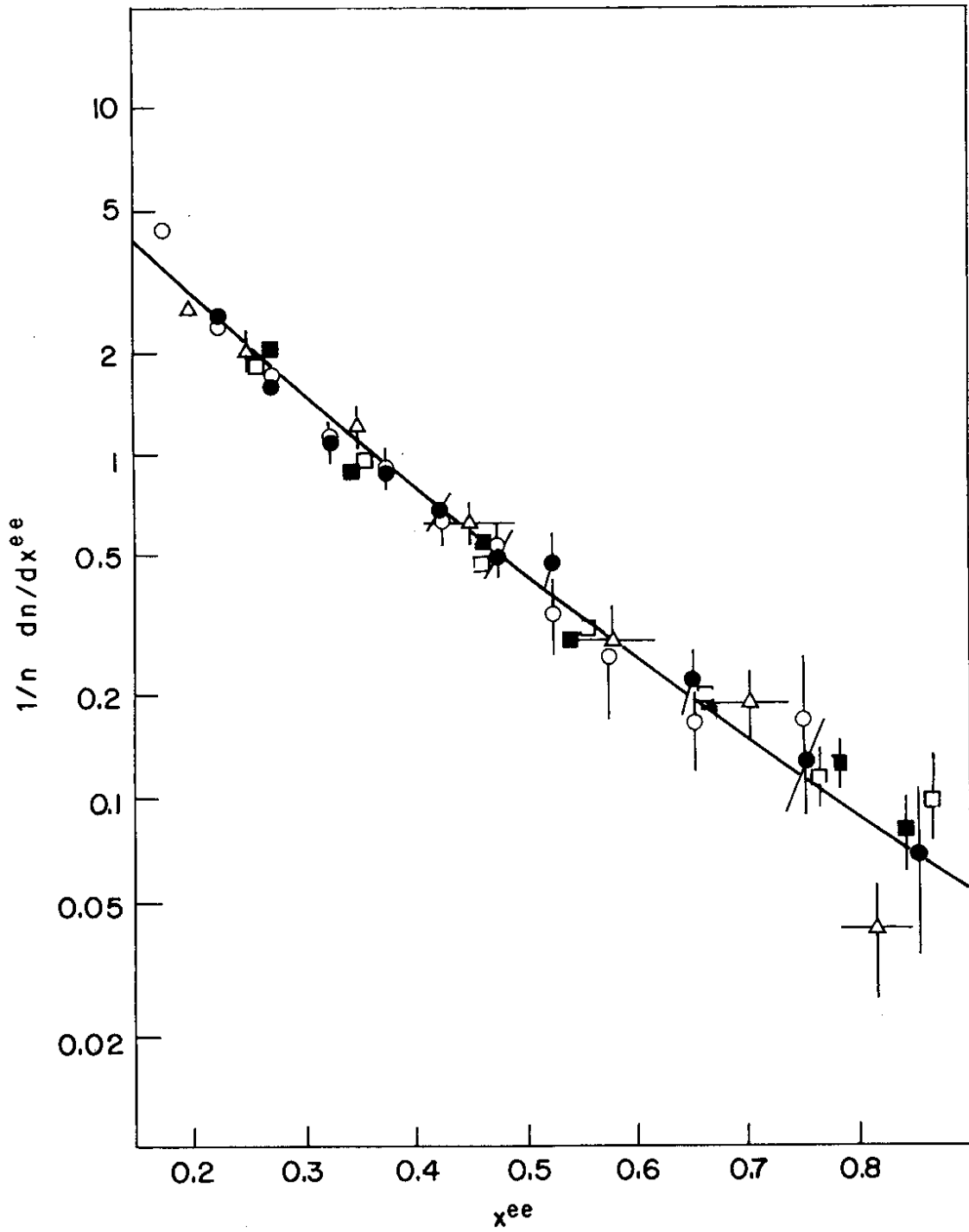


Fig. 21

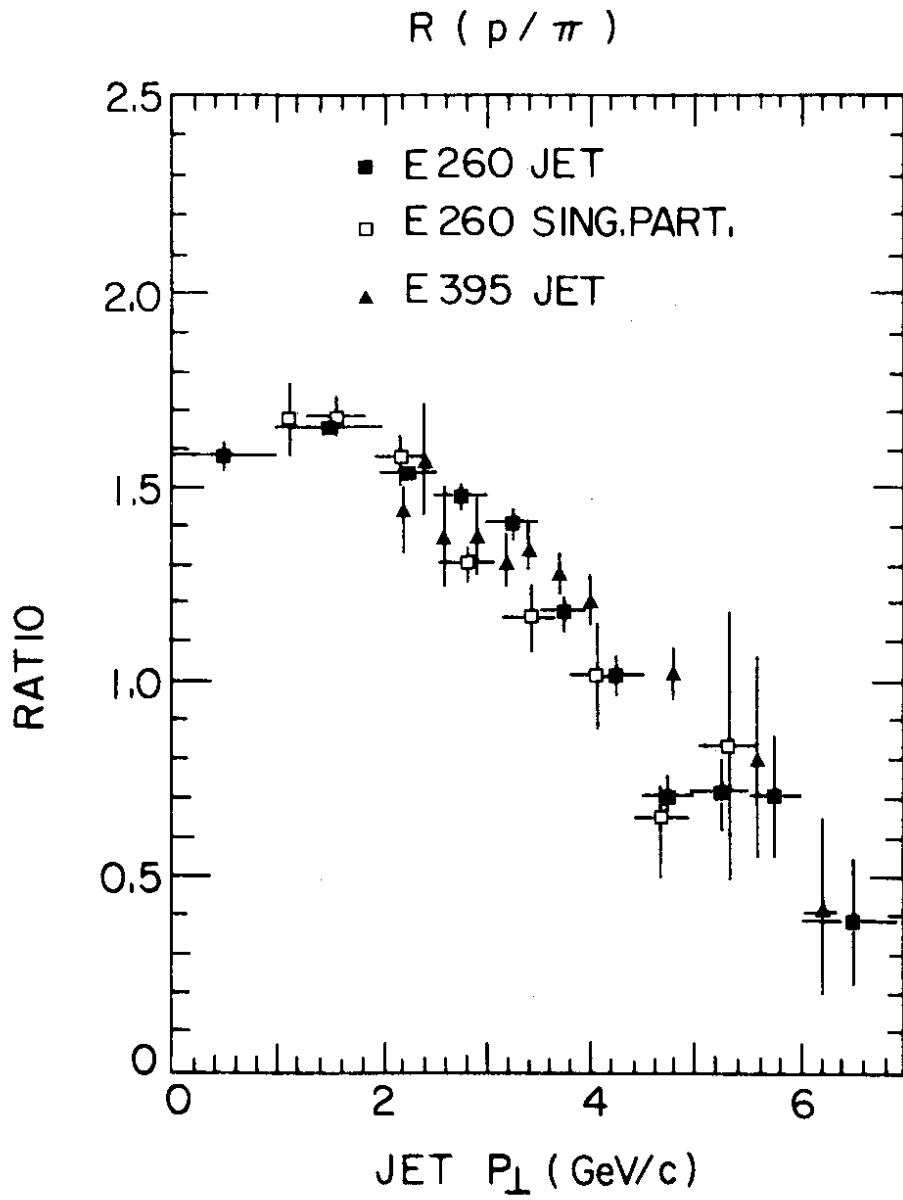


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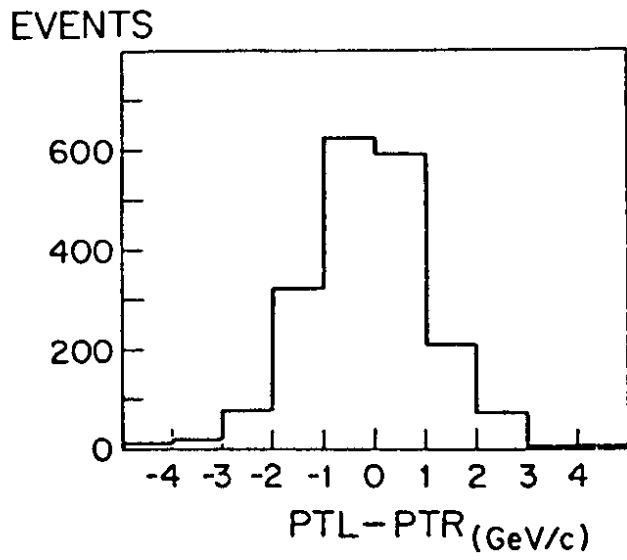


Fig. 23

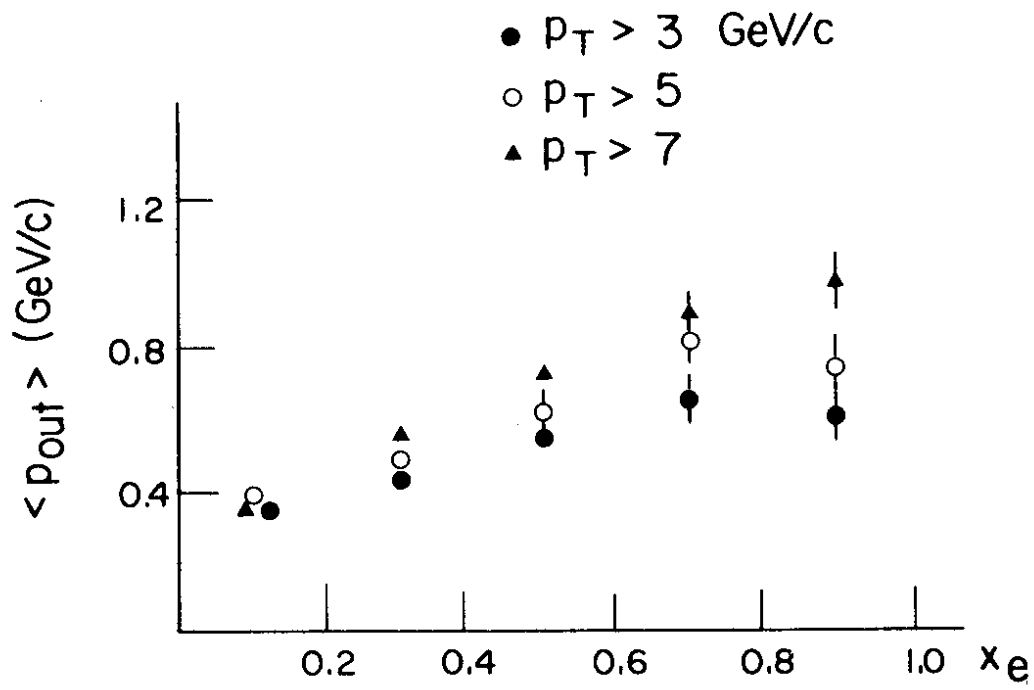


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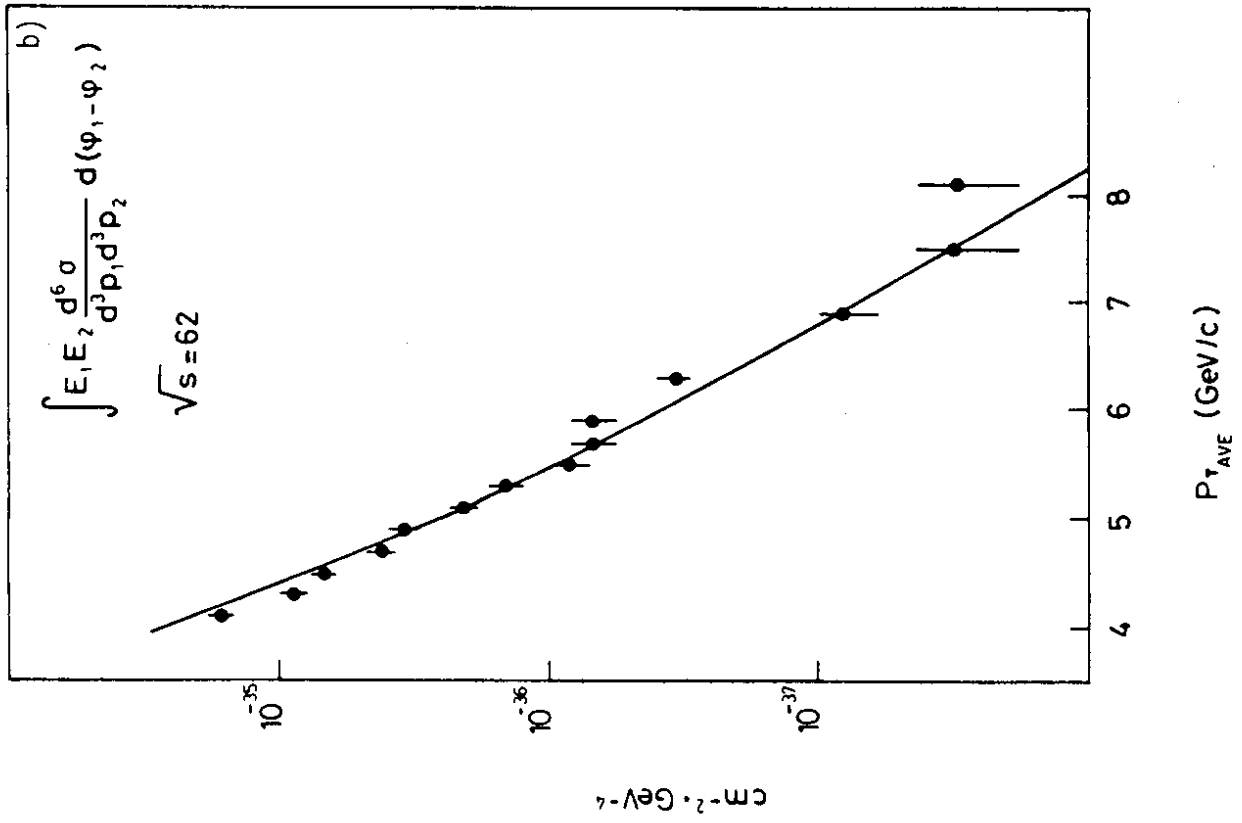
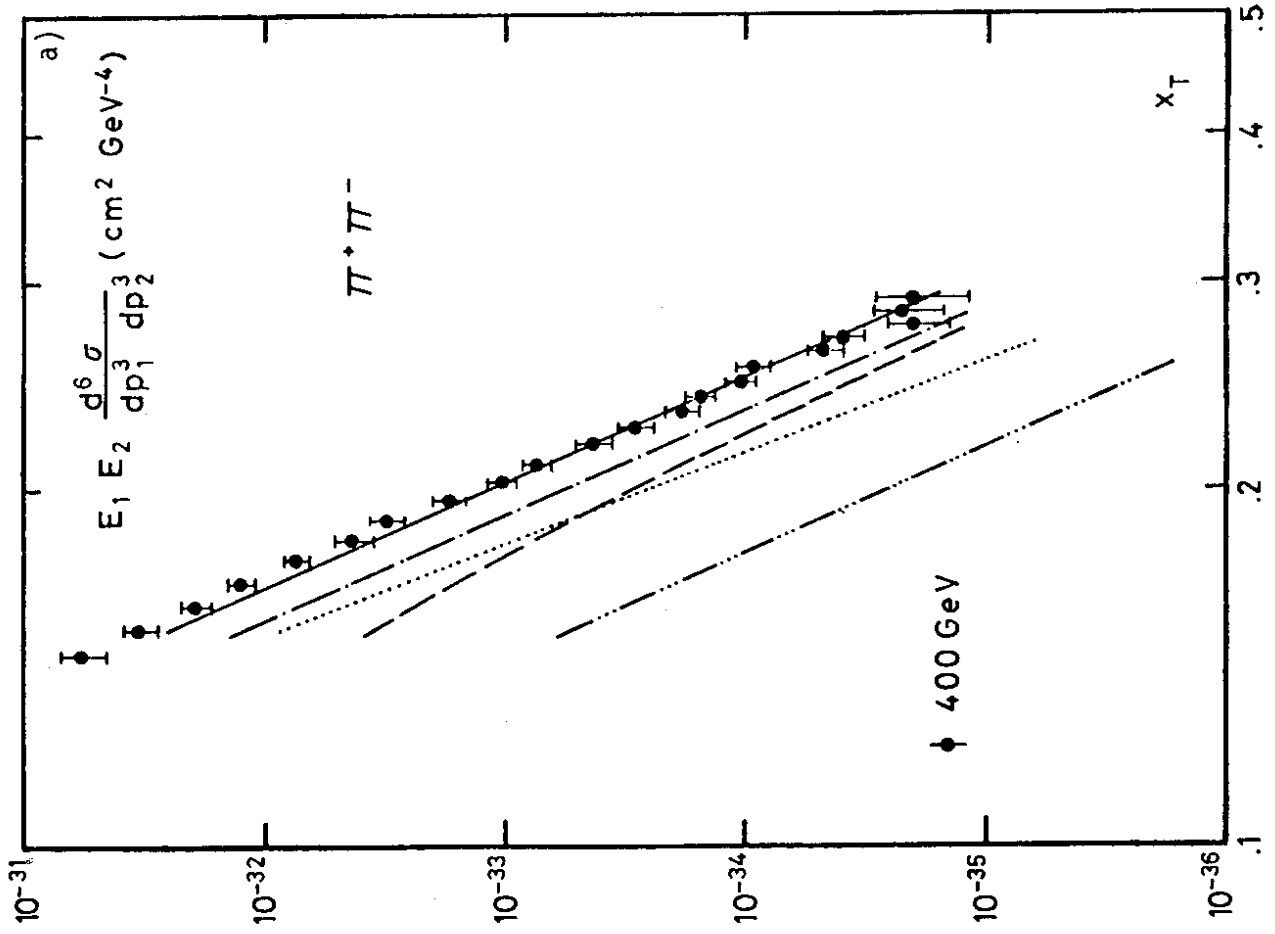


Fig. 25

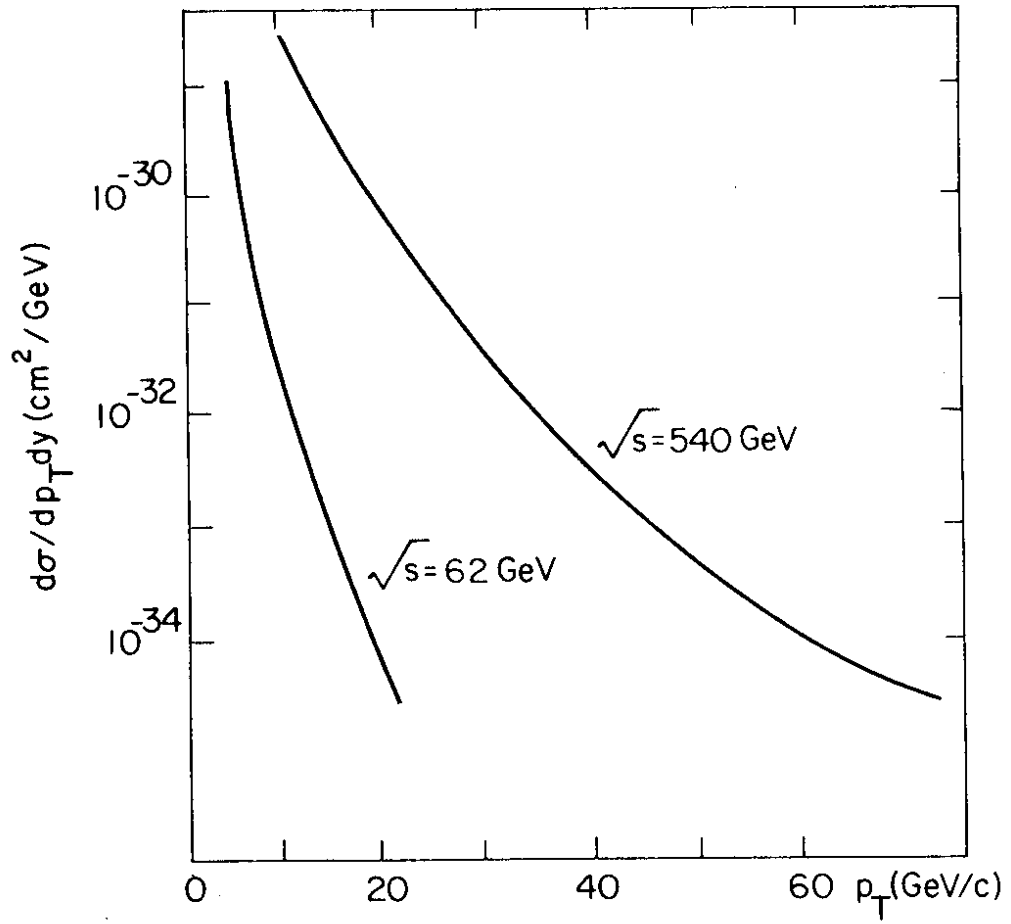


Fig. 26

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